ILLUMINATION AND PHOTOMETRY

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BY

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PREFACE

THE preparation of this volume was undertaken with a view to providing an adequate text-book of the subject for the use of colleges of engineering. It is not intended to be a handbook of technical data nor a manual of practical instructions. Emphasis is therefore given to the scientific basis of the subject and to methods of rational analysis rather than to the description of processes of manufacture, structural details and prevailing practice. A condensed form of treatment has been sought throughout. In the work of instruction much of the subject-matter may profitably be amplified by lectures, supplementary reading and the working out of problems. Familiarity with the technique of photometry should be sought in the laboratory in connection with such a course.

The material herein contained to a large extent represents the basis of a course in Illumination and Photometry given by the University of Wisconsin, and the author acknowledges with pleasure much helpful encouragement and many suggestions from Prof. Murray C. Beebe of that institution.

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CHAPTER I.

THE PRODUCTION AND PROPAGATION OF LIGHT.

Light defined.—The term *light* is employed in two senses, viz., subjectively, to denote the sensation characteristic of the retina of the eye, and objectively, to denote the physical cause of that sensation. These two uses are to be regarded as supplementary rather than contradictory. For the purposes of this work light may be considered as a physical phenomenon of the ether, measured in terms of the visual sensation which it is capable of exciting.

Radiation.—A body may dissipate its molecular energy by three processes, conduction, convection and radiation. The two former result from intimate contact with some other body at a lower temperature. The latter consists of a vibratory disturbance of the ether propagated in all directions from the radiant source with a velocity of 188,000 miles per second. Radiation is exceedingly complex and involves a great variety of waves differing in length, frequency and intensity. This entire group of waves is known as the *spectrum*. The length of radiant waves is conveniently measured in *microns*, a unit which has the value of 0.001 mm. and is denoted by the symbol μ. For convenience the spectrum may be considered as made up of three regions distinguished by the physiological effects to which they give rise. Their boundaries are indistinctly defined and the limiting wave-lengths are somewhat arbitrarily chosen. Accordingly, the infra-red region includes all waves of greater length than 0.8 μ, commonly called heat waves; the luminous region extends from 0.8 μ to 0.4 μ; and the actinic or ultra-violet region, characterized by the chemical activity stimulated by its waves, includes all waves shorter than 0.4 μ.

Incandescence.—Light derived from bodies in the solid and molten states is generally due to the phenomenon of incandescence. A heated body tends to equalize its temperature with that of its surroundings by the radiation of its energy. Its spectrum includes all wave-lengths, but at low temperatures the proportion of the radiation in the visible region is too low to stimulate the eye. As the temperature of the radiant is increased, the proportion of luminous radiation increases until sufficient to produce visual sensations, first of dull red, and, as the temperature mounts still higher, the intermediate tints of red, orange and finally of dazzling white.

The energy distribution among the waves of the incandescent spectrum is dependent upon the material of the source and its temperature. The intensity P at any wave-length of the radiation emitted by a black body at an absolute temperature T is given by Planck's law as

$$P = k_1 l_w^{-5} \left(\varepsilon^{\frac{k_2}{l_w T}} - 1 \right)^{-1},$$

k_1 and k_2 being constants and ε the natural logarithmic base. Energy distribution curves for different temperatures are indicated in Fig. 1. Inspection of these curves shows that the

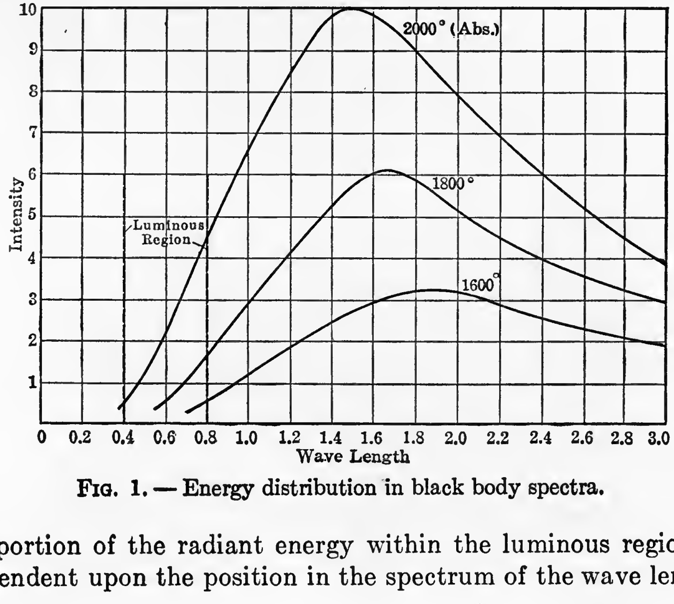


Fig. 1.—Energy distribution in black body spectra.

proportion of the radiant energy within the luminous region is dependent upon the position in the spectrum of the wave length

of maximum intensity. For a black body at an absolute temperature T the wave length of maximum intensity is

$$l_{w_{max}} = \frac{2940}{T},$$

indicating that a temperature of approximately 5000 deg. cent. would be required to produce black body radiation with the greatest intensity near the middle of the luminous region. At some such temperature the proportion of luminous radiation would reach its maximum theoretical value. Even under these most favorable conditions, which far exceed the present limits of attainability, probably not more than from 15 to 20 per cent of the energy expended could be recovered as light. Light produced by black body incandescence is therefore of inherently low efficiency and is in reality a by-product of the production of radiant heat.

Selective radiation.—Such materials as distribute radiant energy through the spectrum in proportions different than those of a black body at the same temperature are said to possess the property of selective radiation or selectivity. In incandescent illuminants this deviation from black body distribution is usually favorable to the luminous region, so that a higher efficiency is obtained than from a black body at the same temperature. For example, the wave-length of maximum intensity in the spectrum of polished platinum is given as

$$l_{w_{max}} = \frac{2630}{T}.$$

Comparing this expression with the corresponding black body law, it is seen that at any temperature T the maximum intensity occurs at a shorter wave-length in the platinum spectrum and that the energy distribution is correspondingly more favorable to light production. Selectivity of this order is possessed by many materials to a degree of practical importance, notably among the rare earth oxides and the refractory metals much used in incandescent lighting.

Luminescence.—As a mode of light production incandescence is characteristic of solid and liquid bodies. Gases may also produce light by incandescence when small particles of solid carbon are liberated in a flame and remain incandescent until

consumed by oxidation or carried out of the zone of combustion as smoke. A very different phenomenon of light production obtains when gases become luminous under the influence of certain electrical, thermal and chemical stimuli, as in the electric arc, the Geissler tube and the sodium flame. It is supposed that these stimuli cause the gas atoms to release their constituent electrons and to project them with enormous velocities into the surrounding gas, inducing vibrations characterized by light emission. This phenomenon is termed luminescence.

In contrast with incandescence, luminescence shows no definite relation between the quantity and quality of its light emission and the temperature of its source. Incandescent light involves the inevitable presence of a larger amount of radiant heat, but pure luminescence may theoretically yield cold light with a very nearly perfect efficiency of energy transformation. Such an illuminant would be ideal if of reasonable simplicity, moderate brilliancy and well-balanced spectrum. While pure luminescence of this order has never been approximated artificially, the luminescent light sources have in some cases attained great superiority in efficiency over the incandescent sources. The possible modes of vibration of electrons in gases are practically limitless in variety. Doubtless there will yet be found some means of inducing luminescence which will far exceed in efficiency all existing methods of artificial light production. Nature has apparently locked up the secret in the firefly, in the spectrum of which only luminous waves are found.

Luminous efficiency is generally used to denote the ratio of the luminous radiation of an illuminant to its total radiation. Inasmuch as the visual intensity of light depends not only upon the quantity of luminous energy emitted but also upon its distribution among the waves of the luminous spectrum, the above definition is not of great direct value. In engineering practice it is customary to express efficacy (misleadingly called efficiency) as the ratio of the light produced to the total energy expended, and is preferably expressed as lumens per watt in the case of electric illuminants and as lumens per cubic foot burned per hour in the case of gas illuminants. The precise determination of the true thermodynamic efficiency of illuminants is beset with great difficulties and the published results show a considerable

degree of variation. Table I gives estimates, derived from the researches of H. Lux, which are of illustrative value.

TABLE I. — EFFICIENCY, SPECIFIC POWER CONSUMPTION AND SPECIFIC OUTPUT OF VARIOUS ILLUMINANTS. (Lux.)[1]

Illuminant.	Watts consumed.	Per cent total radiation between 0.4 μ and 0.8 μ	Per cent power radiated as light.	Mean spherical candle-power.	Watts per m.s.c.p.	Lumens per watt.
Hefner lamp	86.3	0.89	0.103	0.726	128.8	0.106
Kerosene lamp	508	1.23	0.25	10.56	48.2	0.261
Acetylene flame	96	6.36	0.65	5.31	18.1	0.695
Gas mantle with chimney	716.7	2.92	0.46	78.9	8.97	1.385
Inverted mantle with glass	571.0	2.97	0.51	72.4	7.88	1.593
Carbon filament lamp	98.23	3.2	2.07	21.6	4.55	2.76
Nernst lamp with ballast	181.4	5.7	3.85	83.5	2.18	5.76
Nernst lamp without ballast	165.0	5.7	4.21	83.5	1.98	6.35
Tentalum lamp	44.0	8.5	4.87	23.5	1.87	6.71
Osram lamp	38.3	9.1	5.36	24.1	1.60	7.91
D.C. open carbon arc	435.0	8.1	5.6	461	0.95	13.3
D.C. enclosed carbon arc	541.0	2.2	1.15	260	2.08	6.04
A.C. carbon arc	180.6	3.7	1.84	96	1.88	6.67
Yellow flame arc	349.7	17.7	15.0	1010	0.343	36.3
White flame arc	148.0	8.6	7.56	668	0.521	22.2
Quartz tube Hg. arc	691.0	17.6	6.0	2640	0.261	48.0

[1] Elec. World, Vol. L, p. 929.

A comparison of the conversion efficiencies given in Table I with those commonly obtained in the realm of electrodynamics reveals an immense field for future discovery and invention. The search for a more efficient source of luminescence is in an empirical stage. In the realm of incandescence, however, improvement upon the existing efficiencies is to be sought in the discovery of a material capable of withstanding a higher sustained temperature or one possessing a more marked degree of selectivity than any now employed. In this connection it is significant to note that the gain in efficiency secured from a relatively small increase of temperature above the present practi-

cal limits would be of great importance and value, as indicated by the curve of Fig. 2.

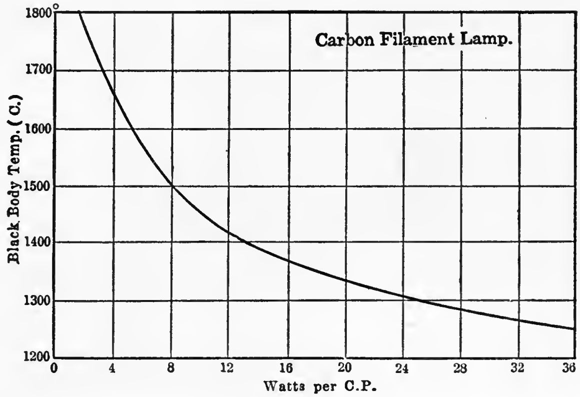


Fig. 2. — The dependence of luminous efficiency upon temperature.

The spectra of all incandescent illuminants are continuous, *i.e.*, all wave-lengths are represented and the distribution of radiant energy is a definite function of the temperature. Luminescent spectra are discontinuous and consist of detached bands, each representing a limited group of wave lengths. The spectrum of each luminescent source is peculiar to the gas employed and the mode of its stimulation.

Phenomena of Light Propagation.

Unless modified by some interfering agency light waves are propagated in all directions from the source along radial lines. At great distances the rays become practically parallel, as in the case of sunlight. From the spherical form of light waves traveling in a medium of uniform density it follows that the intensity of light is inversely proportional to the square of the distance from its source. This fundamental *law of inverse squares* applies strictly only to light emanating from a true point source. For finite radiating surfaces the law holds to a close degree of approximation at a distance from the source greater than ten times its maximum apparent dimension. At shorter distances the application of this law involves serious error, as shown in Fig. 3.

When the direction of light rays is altered by a reflecting surface in a perfectly regular manner so that the continuity of the

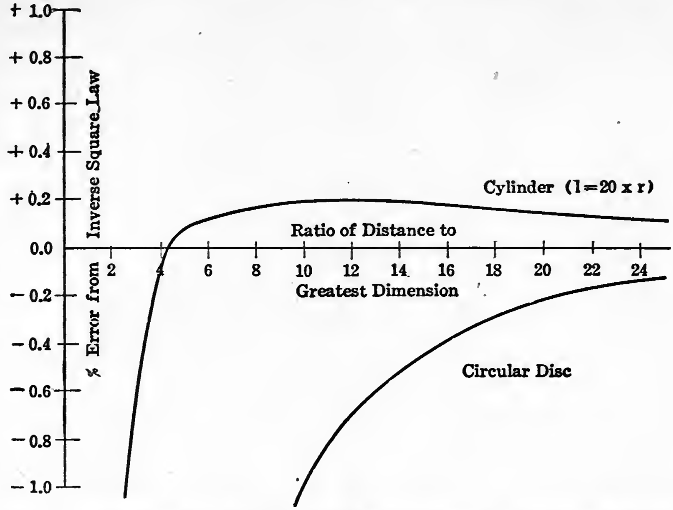


FIG. 3. — Application of the inverse square law to finite light sources.

waves is unbroken, the reflection is said to be *regular* or *specular* and is governed by the familiar law:

$$\alpha_i = \alpha_r,$$

α_i and α_r being respectively the angles of incidence and reflection. Regular reflection may be recognized by the characteristic formation of an image of the light source. Special cases of regular reflection occur when the reflecting surface is plane, concave, convex, spherical, parabolic, etc.

Diffuse reflection occurs when rays of light fall upon an irregular surface such as ground glass, plaster or paper and are scattered in all directions as though having their origin at the reflecting surface, which itself appears luminous and forms no image of the primary source. According to *Lambert's cosine law*[1] a perfectly diffusing surface radiates light in every direction with an intensity proportional to the cosine of the angle of emission, measured between the beam and the normal to the surface. The physical basis of this law may be illustrated by the fact that a luminous spherical surface appears to the eye to be a circle

[1] Phil. Mag., Feb., 1900, p. 199.

of uniform brightness and that a luminous plane surface appears equally bright from whatever angle it is viewed, as its apparent area is then proportional to the cosine of the angle between the line of vision and the normal to the surface.

Regular reflection and diffuse reflection often occur simultaneously, the proportion of each depending upon the degree of polish of the surface, as may readily be observed with pieces of paper of unequal degrees of glazing. Such surfaces may be at wide variance from the cosine law. Close adherence to this law is necessary in many of the reflecting surfaces employed in photometric measurements. Such surfaces may be prepared from plaster paris, barium sulphate, milk glass and other white materials of fine grain by careful treatment to eliminate all

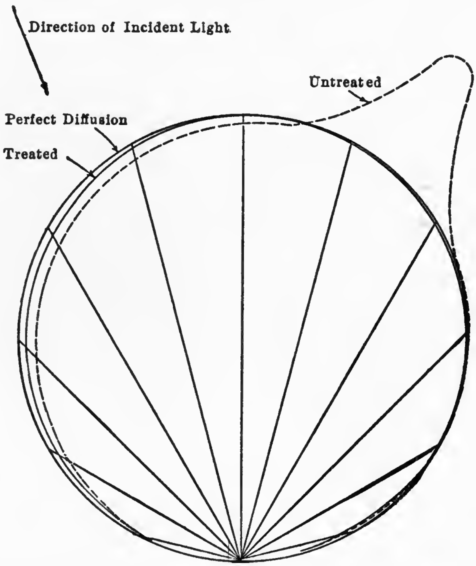


FIG. 4. — Reflection from plaster paris before and after scraping.

surface glaze. Fig. 4 shows the result of such treatment upon a plaster paris surface.

No surface reflects all the light incident upon it, for a portion is always either transmitted or absorbed. In relatively few cases are surfaces found to possess the same degree of reflecting power for all wave-lengths of light. Such surfaces are either white, gray or black. All other surfaces possess the property of *selective*

reflection and owe to it their characteristic color appearance. A red surface, for example, is one reflecting a preponderance of red rays and absorbing large proportions of all other colors.

The ratio of light reflected by any surface to that incident upon it is known as its *coefficient of reflection.* This coefficient has a value dependent upon the physical character of the surface and, when its reflecting power is selective, upon the color composition of the incident light. Thus a surface of high reflecting power for red might show a high reflection coefficient under the light of the carbon filament lamp and practically zero reflection coefficient under the green light of the mercury arc. Coefficients of reflection are best stated in terms of daylight and special determinations or a due allowance should be made when dealing with light of any other color. Table II gives approximate results collected by Bell.

TABLE II. — COEFFICIENTS OF REFLECTION. (Bell.)[1]

Material.	Coefficient of Reflection.	Material.	Coefficient of Reflection.
Highly polished silver	0.92	Yellow painted wall (clean)	0.40
Mirrors silvered on surface	0.70 to 0.85	Light pink paper	0.36
Highly polished brass	0.70 to 0.75	Yellow cardboard	0.30
Highly polished copper	0.60 to 0.70	Light blue cardboard	0.25
Highly polished steel	0.60	Brown cardboard	0.20
Polished gold	0.50 to 0.55	Plain deal (dirty)	0.20
Burnished copper	0.40 to 0.50	Yellow painted wall (dirty)	0.20
White blotting paper	0.82	Emerald green paper	0.18
White cartridge paper	0.80	Dark brown paper	0.13
Ordinary foolscap	0.70	Vermilion paper	0.12
Chrome yellow paper	0.62	Blue-green paper	0.12
Orange paper	0.50	Cobalt blue	0.12
Plain deal (clean)	0.40 to 0.50	Deep chocolate paper	0.04
Yellow wall paper	0.40	Black cloth	0.012
		Black velvet	0.004

[1] Standard Handbook for E. E., 1908, sects. 12–37.

Transmission of light.—A set of phenomena analogous in every way to those characterizing reflection occur in the transmission of light. Thus we have regular and diffuse transmission, occurring respectively with transparent and translucent media; selective transmission yields the appearance of characteristic color; coefficients of transmission have a meaning analogous to those of

reflection and are similarly dependent upon the selective power of the medium. Lambert's law of the cosine applies equally to light diffused in transmission as in reflection.

Under the head of regular transmission may be noted two important phenomena, refraction and total reflection. Light in passing from one medium into another of different optical density undergoes a change in velocity. When this change affects all portions of a wave simultaneously the direction of the wave remains unchanged, but when waves enter a denser medium at an angle other than normal to the surface the direction of propagation is changed according to the law

$$\text{Sin } \alpha_i = K \text{ Sin } \alpha_r,$$

α_i and α_r being respectively the angles of incidence and refraction, measured between the beam and the normal to the refracting surface. K is a constant, known as the index of refraction of the refracting medium. When refraction occurs from a denser medium such as glass into air the path of the beam is determined by the law

$$K \text{ Sin } \alpha_i = \text{Sin } \alpha_r.$$

Should the value of α_i be such that K Sin α_i equals unity, the value of α_r becomes 90 deg. and the path of the refracted beam lies along the surface. α_i is then said to be at its critical value, which may be denoted by α_{i_0}. If α_i exceeds the critical value the beam evidently cannot leave the refracting surface and is reflected by it back into the denser medium according to the law of regular reflection. Various stages of refraction and total reflection are indicated in Fig. 5.

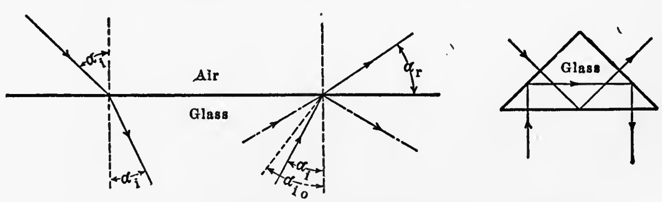


Fig. 5. — Various stages of refraction and total reflection.

Totally reflecting prisms of the type indicated are of great utility in photometric measurements and in prismatic reflectors. They may be made superior to mirrors in the degree and permanence of their reflecting power.

Absorption.—All materials possess to some degree the power of absorbing luminous energy and converting it into molecular heat. Absorption plays an important part in determining the value of materials used as reflectors and diffusers of light. Properly employed the principle of selective absorption is of value in shades designed to balance the spectra of illuminants. Coefficients of absorption express the ratio of the light absorbed in the medium to that incident upon it. As in the cases of transmission and reflection these coefficients may be affected to a considerable degree by the color composition of the incident light. Except in special cases coefficients of absorption should be expressed in terms of daylight.

CHAPTER II.

CONCEPTS, UNITS AND TERMINOLOGY.

Concepts.—Light involves two factors, objective physical energy and subjective visual sensation. For all practical purposes it is desirable that light be measured in terms of the latter factor rather than the former. This is due primarily to two facts, viz., that waves of light having different positions in the spectrum stimulate retinal sensations to very unequal degrees and that the measurement of luminous radiant energy is a difficult and delicate process. The c.g.s. system of units rests upon a rigidly objective physical basis and is entirely inapplicable to quantities involving both objective energy and subjective sensations. The science of illumination has therefore been based upon an arbitrary and utilitarian system of units, derived from the light-giving powers of certain standard light sources.

Quantity of light is measured in units of *luminous flux* and is designated by the symbol ϕ. *Luminous intensity* denotes the intensity with which light flux is emitted by a radiant in a single direction, and is designated by the symbol I. *Illumination* denotes the density of the light flux incident upon an area, and is measured by the units of flux incident upon unit area. Illumination is denoted by the symbol E. *Luminosity* expresses the brightness of surfaces from which light arises as the result of either light emission or light diffusion. Luminosity is measured by the light flux emitted per unit area. The luminosity of primary light sources is referred to as *intrinsic brilliancy* or as *specific intensity,* terms which generally denote the luminous intensity per unit area of the light source.

Luminous intensity admits of the most ready and accurate measurement of all the photometric quantities, and its units form the basis of definition of the remaining units of the system. Further sanction for such definition is derived from the historic fact that the units of luminous intensity have been longest and most widely employed. In the English-speaking world the unit

of luminous intensity is the *candle-power*, originally derived, as the term implies, from the luminous intensity of the candle flame. In Germany the unit of luminous intensity is the *hefner*, denoting the standard intensity of the hefner lamp. In France the units employed are the *carcel*, denoting the standard intensity of the carcel lamp, and the *bougie decimale*, a unit of the same order as the candle-power and defined as 0.104 carcel.

The present value of the candle-power as practically employed in the United States is that established by standard incandescent electric lamps maintained by the National Bureau of Standards. This definition of the candle-power has been arrived at as the result of an evolution of more than a century, of which some of the more recent and significant steps may be noted. Acting upon the accumulated evidence of the unreliability of the candle as a standard luminous source, the American Institute of Electrical Engineers[1] defined the candle-power by the relation, "the *hefner* under standard Reichsanstalt conditions equals 0.88 *British candle*." The accepted value of the candle-power in the gas industry was defined by the British Engineering Standards Committee as one-tenth the intensity of the Vernon Harcourt pentane lamp. As so defined the candle-power was equal to 1.095 hefners, a value about 4.1 per cent lower than that of the A. I. E. E. definition. To remove this discrepancy the National Bureau of Standards was authorized jointly by the Illuminating Engineering Society, the American Institute of Electrical Engineers and the American Gas Institute to establish and maintain a uniform value of candle-power for the United States.

The relative values of the Harcourt unit, the hefner and the carcel were defined by the International Photometric Commission in 1907 as follows:

	Carcel	*Hefner*	*Harcourt*
Carcel	1.000	10.75	0.980
Hefner	0.093	1.00	0.0915
Harcourt	1.020	10.95	1.000

American interests had not been consulted in the formulation of these definitions. An investigation of the relative values of the standards maintained by the official standards laboratories of Europe and America was undertaken by the United States Bureau of Standards and international coöperation sought in

[1] Trans. A. I. E. E., Vol. XIV, p. 90; also Vol. XIX, p. 1089.

the establishment of a uniform unit. The success of these negotiations led to the establishment of the following simple photometric relations effective after April 1, 1909, at the national standards laboratories of Great Britain, France and America:

1 International candle = 1 Pentane candle.
1 International candle = 1 Bougie decimale.
1 International candle = 1 American candle.
1 International candle = 1.11 Hefner unit.
1 International candle = 0.104 Carcel unit.
1 Hefner unit = 0.90 International candle.

The above definitions have been submitted to the International Electrotechnical Commission in anticipation of their acceptance by all the nations represented in the commission.

Luminous flux.—A luminous source radiating flux with unit intensity in all directions gives forth unit luminous flux within each unit solid angle. A unit solid angle may be defined as the angular space subtended at the center of a sphere by an area of its surface equal to the square of its radius. The total angular space about a free point therefore equals 4π or 12.5664 solid angle units. The unit of luminous flux above defined is known as the *lumen.* The value of the lumen is dependent upon the value of the unit of luminous intensity upon which it is based. The term lumen as used throughout this work applies only to the value derived from the American standard candle-power.

The light of a source whose average intensity in all directions is one candle-power is said to equal one *mean spherical candle-power* or one *spherical candle.* This term is commonly used as a measure of mean luminous intensity, but it obviously refers to a definite quantity of light flux with a value of 12.5664 lumens.

Illumination.—The term illumination has been defined as denoting the density of the light flux falling upon a surface. Unit illumination logically denotes unit flux incident upon unit area. The unit commonly employed in America is the *foot-candle,* denoting an illumination of one lumen per square foot. The foot-candle may also be defined as the illumination received by a surface at every point one foot distant from a light source of one candle-power. An illumination of one lumen per square meter is known as a *lux* or a *meter-candle,* terms most commonly employed in Europe. One foot-candle equals approximately 10.8 luces.

From the law of inverse squares and the law of cosines it is evident that the illumination at a point may be expressed in terms of the intensity I acting in its direction, the distance l between the light source and the point illuminated and the angle θ between the beam and the normal to the surface at the point, thus:

$$E = \frac{I \cos \theta}{l^2}.$$

Luminosity.—It has been seen that illumination measures the density of the flux incident upon any surface. Luminosity measures the density of the flux arising from a surface either as the result of light emission or light diffusion. Luminosity is conveniently measured in lumens emitted per square foot, but the significance of the term when so employed should be clearly stated to avoid confusion with illumination. The luminosity of a diffusely reflecting surface equals its illumination multiplied by its reflection coefficient. Similarly the luminosity of a diffusely transmitting surface equals its received illumination multiplied by its coefficient of transmission.

The intrinsic brilliancy of light sources may be expressed as the lumens emitted per square foot of radiating surface or as the candle-power per square inch of surface exposed in a given direction, the latter form of expression being the more common.

Summary.—The relations of the units of light are summarized in Table III.

TABLE III. — MUTUAL RELATIONS OF PHOTOMETRIC CONCEPTS AND UNITS.

Concept.	Symbol.	Unit.	Defining Relation.
Intensity........	I	Candle-power.......	$I = \frac{d\phi}{d\omega}.$
Quantity........	ϕ	Lumen.............	$\phi = I\omega = 4\pi I_{ms}.$
Quantity / Mean intensity	I_{ms}	Spherical candle....	$I_{ms} = \frac{\phi}{4\pi}.$
Illumination.....	E	Foot-candle........	$E = \frac{\phi}{A}.$ $E = \frac{I \cos \theta}{l^2}.$
Luminosity......	L	....	$L = \frac{\phi r}{A}$, or $L = \frac{\phi t}{A}.$
Brilliancy.......	e	....	$e = \frac{I}{a}.$

NOTE. — ω = solid angle units. A = Area illuminated (sq. ft.). a = Apparent luminous area of source (sq. in.) r = Coefficient of diffuse reflection. t = Coefficient of diffuse transmission.

CHAPTER III.

STANDARD LUMINOUS SOURCES.

The value of any system of units is determined by the accuracy with which they may be realized and reproduced in actual measurement. A primary unit is one which may be reproduced with absolute inerrancy by fulfilling definite specifications. The physical agency employed in its realization may be termed a *primary standard.* The essential criterion to be met by a primary standard of luminous intensity is the production of light of a definite intensity and of satisfactory spectrum by a definite physical phenomenon every feature of which admits of precise reproduction. Those standards which possess approximate reproducibility and whose variations from a state of constancy are accurately known may be termed *secondary standards. Comparison standards* are those which remain sensibly constant when calibrated in terms of standards of higher order.

Proposed primary standards.—The exhaustive investigation devoted to the problem has as yet produced no primary luminous standard worthy of final acceptance. Violle attempted to meet the above criterion by a *platinum standard,*[1] the standard intensity being that emitted normally by a square centimeter of molten platinum at the temperature of solidification. This proposal was formally accepted and subsequently discarded. It is not certain that the solidification of the metal occurs at a definite and invariable temperature, and its light emission is known to be affected by surface contamination.

More recently it has been proposed to define the primary luminous standard as the intensity of a square centimeter of a black body at the temperature of solidification of platinum.[2] The worth of the proposal has not been experimentally verified.

Steinmetz has proposed a novel synthetic standard,[3] whose

[1] Annales de Chimie et de Physique, (6), III, p. 73.

[2] Elec. World, Vol. LII, p. 625.

[3] Trans. A. I. E. E., Vol. XXVII, p. 297.

intensity shall be that resulting from the synthesis of three narrow bands of red, green and yellow light derived from the spectra of mercury arcs. It is proposed that the radiant energy of each band be accurately specified so that their resultant may have a definite and constant luminous value. As yet this proposal lacks the necessary experimental confirmation.

The above-named proposed primary standards involve a degree of difficulty in manipulation which would quite disqualify them for routine testing. This fact does not impair their possible value. Such standards might be maintained by the national standardizing laboratories of Europe and America as the ultimate basis of the calibration of secondary standards and comparison standards of great simplicity. Flame standards belong properly in the secondary class, as the physical conditions of combustion cannot be regulated with the requisite certainty to give them status as primary standards. In the present state of the art, however, they are of indispensable value.

Working standards.—The candle, which for more than a century and a half has furnished the popular conception of the unit of light, is entitled to historical veneration, but may be classed among standards only with mental reservations. In common with all flame illuminants it is subject to variation in intensity with the pressure, the humidity and the degree of vitiation of the atmosphere for which accurate correction cannot always be made. Although a vast amount of research has been expended upon the candle, and its dimensions and the mode of its manufacture[1] have been carefully specified, it has proven incapable of yielding the constant and definite intensity required of a standard.

Candles are still extensively used in the routine testing of gas. They are commonly mounted in pairs upon a candle balance, the two wicks being bent at right angles. They are assumed to yield their standard intensity when each is burning at the rate of 120 grains per hour. Photometric observations are taken during the period required for the consumption of 40 grains of sperm, which should normally be ten minutes. Should the actual rate of combustion differ from the standard rate by not more than 5 per cent, the intensity of the candles is corrected in direct proportion to the consumption of sperm. When used with care

[1] American Gas Light Journal, 1894, Vol. 60, pp. 41 and 326.

candles are capable of yielding consistent results. They are discredited, however, for all photometric work of importance.

The hefner lamp[1] is the legal standard of luminous intensity for the German empire, and its prototype is maintained by the Physicalische Reichsanstalt. The details of its structure are embodied in strict specifications, and the variations of its intensity with atmospheric conditions and the rate of combustion have been exhaustively studied. Its advantage as compared with other standards is not so much its invariableness as the accuracy with which it can be reproduced and the certainty with which its performance can be corrected to standard conditions. The combustible employed is amyl acetate, a definite chemical compound readily obtainable in the pure state. Amyl acetate vaporizes at a temperature so low that its combustion is but little affected by the character of the wick.

The structure of the hefner lamp is indicated by a vertical section in Fig. 6. Certain of the dimensions must be adhered to with the greatest precision, particularly those of the wick tube and the height of the flame gage. A flame height of 40 mm. must be accurately maintained. This height is checked by the image of the flame tip formed on a ground-glass screen in the flame gage, the correct height being indicated by an etched line. A test gage may be slipped over the wick tube to test the accuracy of the flame gage. The top of the test gage is beveled to a true horizontal edge whose image in the flame gage should show exact coincidence with the etched line. With the test gage so set there should be the least possible clearance between the top of the wick tube and the top of a horizontal slit through the gage.

To prepare the lamp for use the top plate is unscrewed and the wick drawn into the tube from beneath by the notched wheels. Its top is trimmed flat and true without projecting fibers. A suitable amount of chemically pure amyl acetate is poured into the lamp body, the top is replaced and the lamp is allowed to stand until the wick is thoroughly saturated. After lighting the flame its height is set from time to time until it burns steadily and correctly, requiring a period of not less than fifteen minutes. The barometric pressure, the atmospheric humidity and, in cases of great refinement, the content of CO_2 in the air are

[1] Elek. Zeit., Vol. 84, p. 20.

carefully determined. After using the lamp is thoroughly rinsed in alcohol and dried and the wick is removed, washed in alcohol, dried and stored in a clean dry place.

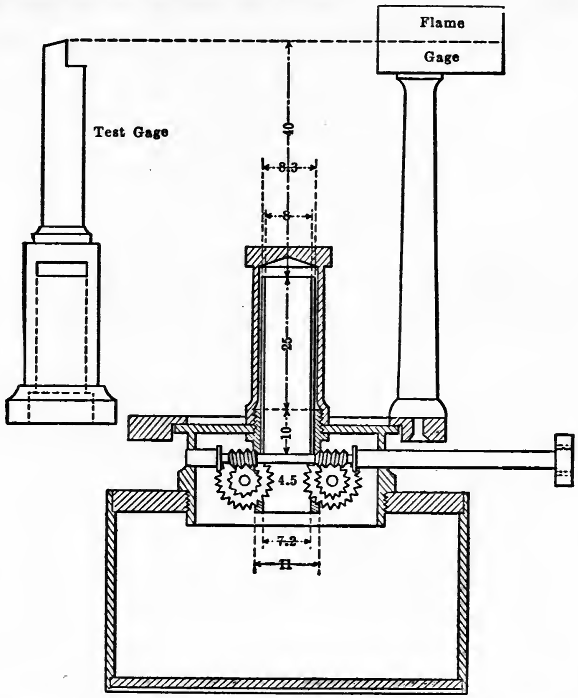


Fig. 6.—Vertical section of the hefner standard lamp.

The standard intensity of the hefner lamp is that given when burning at a barometric pressure of 76 cm. in an atmosphere containing 8 liters of water vapor per cubic meter. In all work of importance correction must be made for all deviations from standard atmospheric conditions.[1] Corrections for barometric variations may be made as follows:

$$I = 1 + 0.00011\,(b - 760),$$

I being the corrected intensity and b the observed barometric pressure in millimeters. Corrections for atmospheric humidity are made as follows:

$$I = 1.049 - 0.0055\,x,$$

[1] Elek. Zeit., Oct. 10, 1895, p. 655.

x signifying the liters of water vapor per cubic meter of air at 76 cm. pressure and free from CO_2. The effect of carbon dioxide upon the intensity is similar to that of water vapor, but is generally negligible in rooms receiving fair ventilation. The correcting equation is as follows:

$$I = 1.012 - 0.0072\,y,$$

y being the liters of CO_2 per meter of dry air at normal pressure.

The flame height of the lamp must be maintained with strict care, a variation in height of 0.2 mm. causing a change in intensity of 0.5 per cent.

The chief objections to the hefner lamp as a working standard are its low intensity, the reddish color of its flame which renders photometric settings difficult and introduces inaccuracies at low intensity by the Purkinje effect, the sensitiveness of its intensity to slight changes in height and the tendency of its flame to waver and flicker with slight atmospheric disturbances. A commentary on the present status of photometric standards is found in the fact that the Reichsanstalt certifies as correct all hefner lamps found to agree with the prototype to within 2 per cent.

Pentane gas standards have found the greatest favor with British photometricians and in the gas industry in America. Pentane is a volatile hydrocarbon which mixes readily with air at ordinary temperatures to form a gas of high and uniform illuminating power. Under carefully regulated conditions it yields a flame of great constancy and excellent color. In low candle-power pentane standards the vapor is supplied to the flame by a wick, but in the most satisfactory types the air gas is formed in a carburetor and is fed to an argand burner, the air supply of which is preheated by the products of combustion.

The Vernon Harcourt standard[1] as employed in American practice is shown in section in Fig. 7. The carburetor is partially filled with pentane over which air is drawn through a long path defined by baffle plates. The saturated air-pentane mixture passes by gravity down a metal tube to an argand burner surmounted at a height of 47 mm. by a cylindrical brass chimney. An annular chamber containing unvitiated air surrounds the chimney and communicates with the burner, supplying the flame with preheated air. A blackened conical hood at the base of the

[1] Proc. British Assoc., 1877, p. 51; also Gas World (London), Vol. 28, p. 951.

chimney protects the flame from drafts, the flame being exposed by a slit running down one side. Just above the conical shield is a mica window with a gage line to whose level the height of the flame is accurately adjusted.

Under normal atmospheric conditions, *i.e.*, a barometric pressure of 76 cm. and a humidity of 8 liters per meter of air, the intensity of the flame is 10 candles. When the pentane lamp is used in the photometry of flames it is assumed that both the standard and the flame tested are equally affected by variations from normal atmospheric conditions, thus avoiding troublesome corrections. For all other work the requisite corrections may be made by the equation

$$I = 10 + 0.066\,(10 - x) - 0.008\,(760 - b).$$

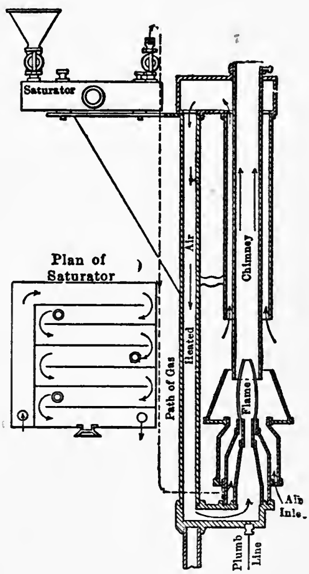


Fig. 7.—The Vernon Harcourt ten-candle pentane standard.

x denotes the number of liters of moisture per cubic meter of air and b the barometric height in millimeters. Correction for the CO_2 of the air may be made by the equation

$$I = 10 - 0.297\,(y - 0.23),$$

y being the liters of CO_2 per meter of dry air at 760 mm. pressure.

The ten-candle pentane lamp is of convenient intensity and excellent color for practical measurements. It is highly accurate in the hands of skilled photometricians. Before its use the lamp should be allowed to burn a sufficient time to attain a uniform intensity and to raise all parts to their equilibrium temperature.

The Carcel lamp[1] is the oldest of the recognized standards and still retains its place of supremacy in France. It has a central-draft ring burner fitted with a wick of the lighthouse type which dips into a tank in which a constant level of oil is maintained. Colza oil, a product of the rape seed, is the combustible employed.

[1] Annales de Chimie et de Physique, (3), Tome XV.

It is consumed at the rate of 42 grams per hour. The flame is surrounded by a clear-glass chimney. When employed with elaborate precautions the Carcel lamp is capable of yielding results comparable with the most modern standards. The bougie decimale, a French equivalent for the candle-power, is defined as 0.104 carcel.

Comparison standards should possess one essential quality, viz., constancy of calibration. With accurate comparison lamps obtainable primary standards need not be of great simplicity nor available in every laboratory. Comparison standards for electric incandescent lamps should be quite independent of atmospheric conditions, but for gas testing the comparison standard should be affected by atmospheric variation to the same degree as the flames to obviate troublesome corrections. They should be standardized to a state of correctness at normal conditions.

The incandescent electric lamp aged by a preliminary burning of at least 100 hours maintains a practically constant intensity for a period of use of from 75 to 100 hours, especially if used at a slightly reduced pressure. Carbon filament lamps selected for standardization should have a specific consumption of not less than 3.5 watts per candle and should be standardized after seasoning at a somewhat reduced voltage. Preliminary investigations indicate the superiority of tungsten filament lamps operated below normal voltage as comparison standards. The Nernst glower possesses an admirable constancy after seasoning and has been used with satisfaction as a comparison standard. The values of the current and voltage at which a comparison lamp yields its calibrated intensity should be recorded and a position index should be provided when the lamp is to be burned in a stationary position. The intensity of a comparison standard so calibrated may be relied upon as long as the standard values of current and pressure are found simultaneously.

Every laboratory should have in its possession at least one standard lamp certified by the National Bureau of Standards or some equally authoritative source, to be used only in checking up the working standards of the laboratory.

No comparison standard for the testing of gas flames has yet proven its entire reliability. The electric lamp is practically disqualified by its independence of atmospheric variations. The **Edgerton standard** consists of an argand gas burner with a glass

chimney surrounded by a brass sleeve in which is cut a horizontal slit extending entirely across the flame. It operates upon the principle that a definite zone of the argand flame has a fixed intensity regardless of the quality of the gas and its rate of combustion within practical limits. This principle has not been substantiated. The Edgerton standard can be relied upon only when calibrated with the particular quality of gas with which it is to be used.

The Methven screen[1] embodies the same principle as the Edgerton standard, though the slit is vertical and exposes a limited area of the most luminous portion of the flame. It requires calibration with the quality of gas with which it is to be employed.

The Elliot lamp[2] was designed to serve as a comparison standard and as such has found some favor. It is a kerosene lamp of the student type in which a brass screen is utilized to expose a definite area of the flame. A flat wick is employed, the corners being clipped to rid the flame of smoky tails. After burning about fifteen minutes the intensity becomes sensibly uniform for a considerable period.

In the commercial testing of gas the use of standard candles still prevails widely, despite the semi-official discouragement of the practice by the American Gas Institute and the National Bureau of Standards. For all gas testing of importance the ten-candle pentane lamp is to be commended.

[1] Journal for Gas Lighting (London), Vol. 32, p. 95; also Vol. 45, p. 718.
[2] Ill. Eng., Vol. I, p. 322.

CHAPTER IV.

THE PRINCIPLES OF VISION.

The obvious purpose of artificial illumination is to permit the eye to exercise its functions readily and successfully at times of inadequate natural light. Adaptation to vision is therefore the primary consideration in the design of illuminating devices. Unfortunately no principle has been more generally neglected. It should be equally the concern of the illuminating engineer to produce illumination with the best possible conservation of eyesight, the best commercial efficiency and the highest artistic effect.

The eye resembles in its general structure a simple camera. It is a hollow sphere on whose rear interior is found the retina, an elaborate structure of nerve terminals sensitive to light. In front is a circular aperture occupied by a converging lens of elastic material, suspended by a circular muscle by whose contraction and distention the focus is adapted to the distance of the objects viewed. In front of the lens is a muscular curtain, the iris, with a circular aperture, the pupil, which tends to adjust its diameter so as to admit to the retina the amount of light best adapted to clear and easy vision.

The retina is of exceedingly complex structure, comprising two classes of nerve terminals known as rods and cones. A theory of color vision now widely accepted holds that the rods are most sensitive to light of low intensity and that the cones become active only in light of a higher intensity in which the rods assume a state of saturation. Three states of vision may be noted, corresponding to three stages of light intensity, viz., rod vision, in which the rods alone are active, extending from the threshold values of intensity up to about 0.01 foot-candle; combined rod and cone vision, extending to an intensity of about 9 foot-candles; and cone vision, at illumination above 9 foot-candles. In a state of rod vision the retina responds most strongly to the shorter wave-lengths comprising the blue region of the spectrum, tending to reduce all objects to the same bluish-gray tint, as in early

dawn. The sensitiveness of the cones is greatest for the yellow waves of the spectrum and diminishes rapidly in passing toward the red and blue ends of the spectrum. In the intermediate stage of vision the relative sensitiveness of the retina to the different wave-lengths varies with the illumination of the field. This variation in relative sensitiveness leads to the so-called Purkinje phenomenon which is a source of difficulty in photometric measurements of lights differing in color. If two surfaces of red and blue tint respectively are compared in a field of diminishing illumination the blue will appear to be unduly emphasized in comparison with the red as the illumination is decreased. Photometric measurements of unlike colors at low

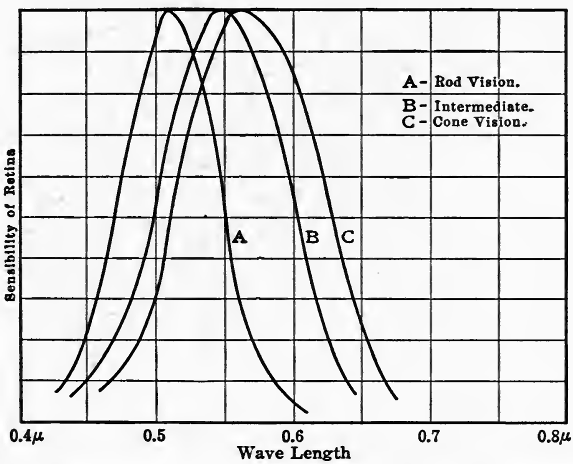


Fig. 8. — Relative sensitiveness of the retina to different wave-lengths.

intensities are therefore to be avoided. Fig. 8 shows the sensitiveness of the retina for various waves of the spectrum at different intensities corresponding to the three states of vision alluded to.

It is evident from the above curves that the spectral composition of light is an important factor in determining its commercial efficiency. At ordinary intensities the conversion of a definite amount of energy into the highly luminous yellow waves yields four times as much light as results from the conversion of the same energy into red or blue radiation.

The sensation of vision, according to Bell, comprises four elementary sensations, viz., contour, relief, perspective, and color. *Contour* involves boundaries, outlines and such other details other than color as assist in the apprehension of flat surfaces. *Relief* is made evident by light and shade caused by different degrees of luminosity. Artists produce the effect of relief by skillful shading. Illumination with an entire elimination of shadows may hinder easy vision by interfering with the perception of relief. For a like reason dense and multiple shadows are to be avoided. *Perspective* arises from the difference in the visual angles subtended by objects at different distances. The sense of *color* is dependent upon the distribution of the radiant energy in the luminous spectrum of the light falling upon the retina and upon the luminosity of the field of view, as before pointed out.

Visual sensitiveness and acuity.—By the term visual efficiency we may denote the ratio of the service rendered by the eye to the expenditure of nervous energy. The proper maintenance of visual efficiency demands attention to two important factors, viz., the sensitiveness of the eye to differences of luminosity and the acuity of the eye, or its ability to distinguish fine detail. Fig. 9 indicates the variation of the sensitiveness of the eye to

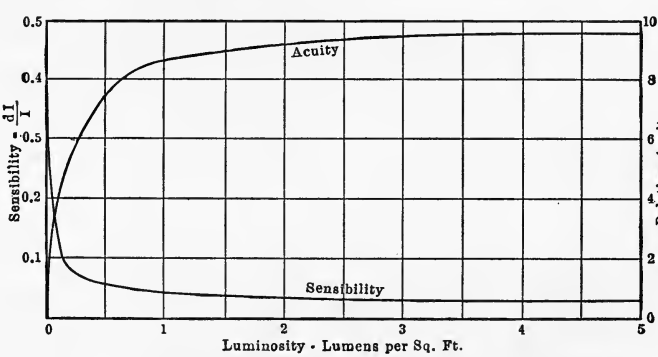


FIG. 9. — Sensitiveness and acuity of the eye for white light.

differences of luminosity and the variation of its acuity with the luminosity of the field when illuminated by white light. It should be noted that both curves rapidly become asymptotic after passing a luminosity of one lumen per square foot. This fact may be summarized into a working principle by which the

degree of illumination required for any surface to meet the ordinary optical requirements may be ascertained, viz., *the illumination of any surface requiring the continued application of the eye shall be such that the light reflected or transmitted by it shall be equivalent to a luminosity of approximately one lumen per square foot.* The gain in visual efficiency obtained from illumination in excess of this standard, though comparatively small, is warranted in cases which make an exceptional demand upon the eye.

Inadequate luminosity and excessive luminosity of the direct field of view are about equally undesirable. In the former case the retinal images are not distinct and the eye grows fatigued in the effort to sharpen their perception. Excessive brightness produces images which are abnormally intense, causing injury to the retina. The pupil contracts in an effort to protect the eye, thus reducing the amount of light entering the eye and rendering the dimmer objects of the field of view indistinct, even though sufficiently bright for normal requirements. Exposed light sources of great intrinsic brilliancy therefore constitute a prolific source of eye trouble when placed directly in the field of view. Optical specialists differ in their estimates of the safe maximum of intrinsic brilliancy for direct vision, the values given ranging from 1.75 to 5 candle-power per square inch of apparent light source.

Direction of light.—The eye has become habituated through the experience of centuries to light coming obliquely from above. The entrance of intense light into the eye from any other direction occasions discomfort and possible injury. The reflected glare from long stretches of snow and water produces irritation and fatigue which bear witness to this fact. Experience has shown that it is well not to place light sources of high brilliancy in such positions that their direct beams enter the eye below the angle of 60 deg. with the horizontal, unless some good diffusing medium is interposed to soften the light. The regular reflection arising from such surfaces as highly calendered paper, polished metal and glazed porcelain produces an annoying glare which may be very harmful if long endured. To avoid this effect the light should be well diffused and its direction given careful attention. Reading, writing and accounting may best be done by light received over the left shoulder to avoid the ill effects of glare.

Steadiness of light.—It has been pointed out that the eye is provided with an automatic screen to regulate the amount of light entering the eye. This screen, the iris, serves as a corrective to varying illumination by its contraction and distention, but its action is not instantaneous, as is painfully evident upon passing quickly from a very dim place to a very bright one. When variations of intensity occur with rapidity and are of considerable magnitude the iris is incapable of equally rapid adjustment and the retina is strained in its effort to maintain clear and uniform vision in the alternately bright and dim light. For this reason illumination from perceptibly flickering lamps may be very injurious. When the rapidity of flicker is such that the eye cannot perceive it no injurious results occur. Visual persistence, or the power of the eye to retain the sensation for a brief instant after the stimulus has ceased, then serves as a corrective. The flicker of light is much more apparent upon an illuminated surface than when the light source is observed directly. A surface which displays no perceptible flicker when at rest may show it to a marked degree when moved, due to the multiple images in the positions at which the light passes through a maximum of intensity.

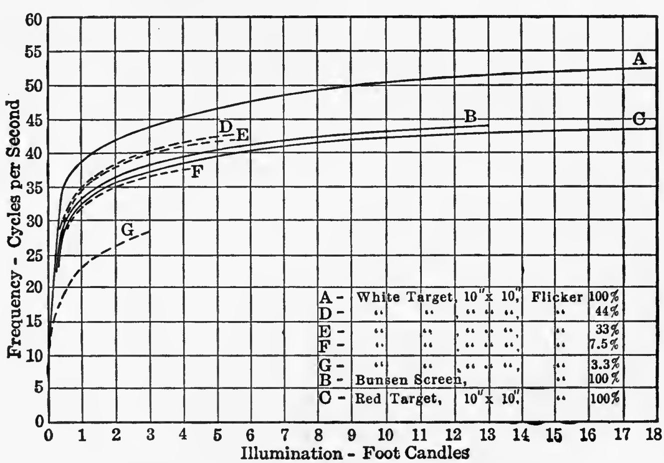


Fig. 10. — Vanishing frequencies of flicker.

The actual frequency of cyclic variation in intensity at which flicker vanishes is a function of several variables, chiefly the mean intensity of illumination of the surface observed, its color and

the extent of the retinal image. The curves of Fig. 10 are based upon the researches of Kennelly and Whiting.

Closely allied to the effects of flicker are those of uneven and streaked illumination. Where the eye must work upon areas of very uneven illumination strain and fatigue soon result. A moderate illumination is much preferable to a higher mean illumination of very uneven character. This statement must be understood to apply to limited areas, such as the top of a desk, rather than to large areas where the light required in different places may vary considerably. Streaked illumination due to heavy shadows and uneven reflection is to be avoided.

Color and vision.—The perception of surfaces in their true relations is jointly dependent upon color and contour. Opaque objects appear in the colors they reflect and translucent materials in the colors they transmit. Our conception of true color values of surfaces is based upon daylight effects. Correct color values cannot be obtained from light lacking any of the components which a surface must reflect to be seen aright, nor can they be obtained from light in which those components appear in proportions strikingly different from those of daylight. For example, the light of the low pressure mercury arc is entirely deficient in red, being composed of yellow, green and violet. It is therefore incapable of showing any but yellowish green surfaces in approximately their true color values. Its effects upon red are startling, making it appear purplish brown.

It is sometimes contended, and not without good reason, that the standard color value for any material should be that obtained with the light in which it is most used. Accordingly the color value of dress goods for street wear should be determined with daylight, while goods intended for evening wear should be judged by artificial light similar in quality to that in which they are to be worn. Obviously the question of color values is one of much importance in the illumination of stores, art galleries, display rooms, etc., and in the selection of colored materials for interior decoration and for clothing. While special standards may be set for exceptional cases it is doubtless true for the majority of cases that true color effects can be obtained only from light possessing approximately the same color composition as daylight.

Color values of illuminants.—In assuming diffused daylight as the standard with which artificial illuminants are to be com-

pared it must be borne in mind that the quality of daylight varies considerably with the location, the time of day and of the year, atmospheric conditions and with adjacent sources of selective reflection. The selection of a standard quality of daylight is necessarily somewhat arbitrary and should represent the best average obtainable. The daylight standard assumed in the following comparisons represents the average of one hundred and fifty sets of spectrophotometric observations made by Prof. E. L. Nichols[1] under a wide range of conditions in both

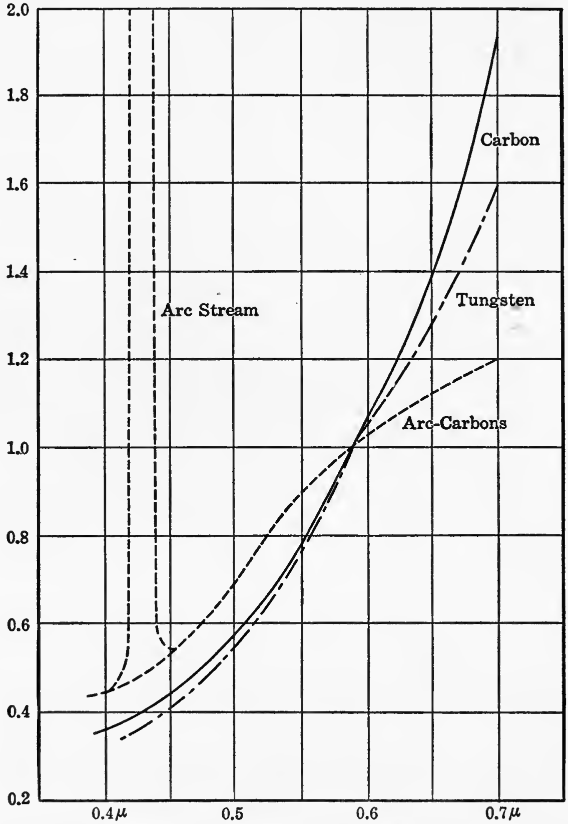


Fig. 11. — Relative spectral composition of daylight and electric illuminants.

Europe and America. The curves of Fig. 11 indicate the relative composition of the spectra of various electric lamps and day-

[1] Trans. Ill. Eng. Soc., Vol. III, p. 301.

light, the intensity of each component of daylight being taken as the basis of comparison with the intensity of the corresponding component of the artificial illuminants.

Similar comparisons are made in Fig. 12 between daylight and gas illuminants.

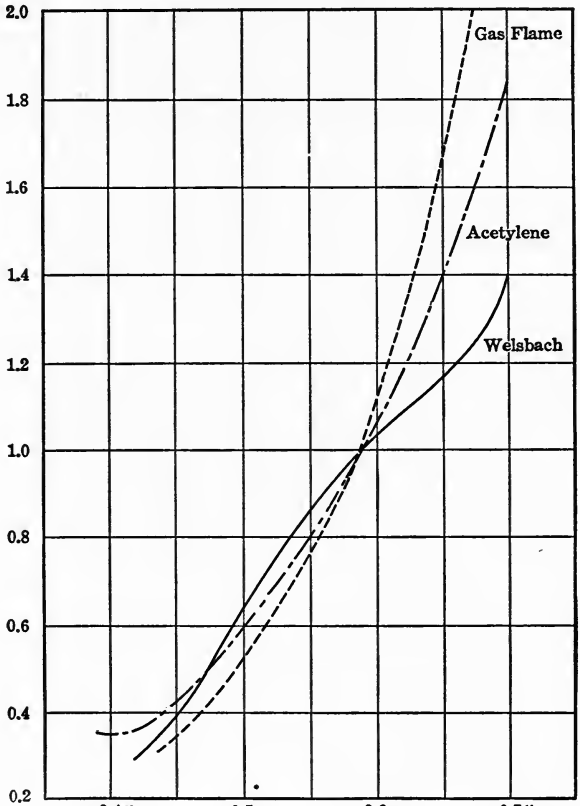


Fig. 12. — Relative color composition of daylight and gas lamps.

The low pressure mercury arc furnishes an excellent example of a discontinuous spectrum from luminescence. It contains but three bands of light, their respective intensities as compared with the same components of daylight being:

Yellow band (0.579 μ to 0.577 μ)	1.00
Green line (0.546 μ)	3.00
Violet line (0.436 μ)	7.85

Colorimeter analyses[1] afford a very practical basis for the comparison of the relative color values of artificial illuminants and daylight. Values for the primary color elements as determined by Ives[2] are given in Table IV.

TABLE IV. — RELATIVE COLOR VALUES OF VARIOUS ILLUMINANTS.
(Ives.)

Source.	Red. Per cent.	Green. Per cent.	Blue. Per cent.
Average daylight	100	100	100
Blue sky	100	106	120
Overcast sky	100	92	85
Afternoon sunlight	100	91	56
Direct current carbon arc	100	64	39
Mercury arc	100 (?)	130	190
Moore carbon dioxide tube [1]	100	120	520
Welsbach mantle (¾% cerium)	100	81	28
Welsbach mantle (1¼% cerium)	100	69	14.5
Welsbach mantle (1¾% cerium)	100	63	12.3
Tungsten lamp, 1.25 watts per mean hor. c.p.	100	55	12.1
Nernst glower, bare	100	51.5	11.3
Tantalum lamp, 2 watts per mean hor. c.p	100	49	8.3
Gem lamp, 2.5 watts per mean hor. c.p.	100	48	8.3
Carbon incandescent lamp, 3.1 watts per mean horizontal candle-power	100	45	7.4
Flaming arc	100	36.5	9
Gas flame, open fish-tail burner	100	40	5.8
Moore nitrogen tube	100	28	6.6
Hefner	100	35	3.8

[1] Trans. Ill. Eng. Soc., Vol. III, p. 635 and p. 643.

Hygienic considerations require in addition to the conditions previously discussed an avoidance of light containing an excess of the chemically active ultra-violet rays. Such rays yield valuable therapeutic effects when skillfully employed, but are equally capable of doing great injury. The question is often raised as to the hygienic importance of strongly unbalanced spectra, such as that of the mercury arc. No direct injury and no indirect benefits appear to arise from their use. It is probable, however, that light which calls into action but a small part of the power of color perception cannot yield continued satisfaction to the eye.

Æsthetic considerations lead to a preference for light with a slightly reddish tinge rather than the cold and searching rays of

[1] See Chapter VI. [2] Trans. Ill. Eng. Soc., Vol. III, p. 631.

pure white or white slightly tinged with green. Blemishes and imperfections are made much more apparent by the colder light. Effects employed upon the stage may be cited as illustrative of these principles, the reddish tints producing a suggestion of warmth, health and cheer, and the faintly greenish tints yielding a cold, cheerless and even ghastly effect.

Psychological impressions frequently play a large part in determining the satisfaction derived from illumination. The absence of visible light sources and of shadows in rooms lighted by indirect methods often leads to a demand for a higher degree of illumination than when exposed lamps are employed, despite the superior uniformity and diffusion of the indirect method. Persons who have become accustomed to a particular type of lamp have been known to complain of the supposed dimness of light when lamps of greater candle-power but of smaller dimensions have been substituted for the familiar type. The principles of association and suggestion may operate to the great annoyance of the illuminating engineer or may be employed by him to very great advantage.

Recapitulation.—The principles of effective vision may be summarized for added emphasis as follows:

(1) The eye works with approximately normal efficiency upon surfaces possessing an effective luminosity of one lumen per square foot or more.

(2) Excessive illumination and inadequate illumination strain and fatigue the eye in an effort to secure sharp perception.

(3) Intrinsic brilliancy of more than 5 candle-power per square inch should be reduced by a diffusing medium when the rays enter the eye at an angle below 60 deg. with the horizontal.

(4) Flickering, unsteady and streaky illumination strains the retina in the effort to maintain uniform vision.

(5) True color values are obtained only from light possessing all the elements of diffused daylight in approximately equivalent proportions.

(6) An excess of ultra-violet rays is to be avoided for hygienic reasons.

(7) Æsthetic considerations commend light of a faint reddish tint as warm and cheerful in comparison with the cold effects of the green tints, though the latter are more effective in revealing fine detail.

(8) Attention is due the psychological laws of association and suggestion.

CHAPTER V.

THE REPRESENTATION AND CALCULATION OF PHOTOMETRIC QUANTITIES.

It is intended to set forth in this chapter certain fundamental relations of photometric quantities which are of importance in the theory of photometric apparatus and in the practical calculations of light and illumination. While many of the relations derived are of fairly apparent physical significance it is believed that their statement in mathematical symbols is of value in showing the logical interrelations of the concepts and units involved.

The law of inverse squares states that the illumination at a point is inversely proportional to the square of its distance from the source of the light. Let dA and dA_1 be elements of surface on concentric spheres of radii l_r and l_{r_1} respectively, surrounding a point source of light as a center. dA and dA_1 are defined by an elementary cone of light flux $d\phi$ emitted within the elementary solid angle $d\omega$. E and E_1 are respectively the resulting illumination of dA and dA_1. The luminous intensity acting upon dA and dA_1 is therefore

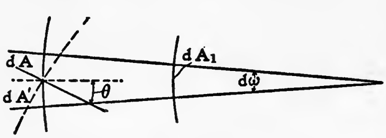


FIG. 13.

$$I = \frac{d\phi}{d\omega},$$

$$dA = d\omega l_r^2 \quad \text{and} \quad dA_1 = d\omega l_{r_1}^2.$$

$$E = \frac{d\phi}{dA} = \frac{d\phi}{d\omega l_r^2} = \frac{I}{l_r^2} \quad \text{and} \quad E_1 = \frac{d\phi}{dA_1} = \frac{d\phi}{d\omega l_{r_1}^2} = \frac{I}{l_{r_1}^2}.$$

The law of the angle of incidence states that the illumination of a surface is proportional to the cosine of the angle of incidence

of the beams received. In Fig. 13 let dA' be an element of surface inclined to dA at the angle θ, then

$$dA' \cos\theta = dA = l_r^2 d\omega,$$

$$E' = \frac{d\phi}{dA'} = \frac{d\phi \cos\theta}{l_r^2 d\omega} = \frac{I\cos\theta}{l_r^2}.$$

Light from a diffusing surface.—Let ϕ be the flux incident upon a diffusing surface of area A and reflection coefficient r, then the reflected flux ϕ', the illumination E and the luminosity of the surface L have the respective values

$$\phi' = \phi r, \qquad E = \phi/A, \qquad L = \phi r/A = \phi'/A.$$

Let I_n denote the normal intensity of the reflected light and e the intrinsic brightness or I_n/A. By Lambert's cosine law

$$I_\theta = I_n \operatorname{Cos}(90 - \theta) = I_n \operatorname{Sin}\theta.$$

Suppose the diffusing surface to be at the center of a hemisphere of relatively large radius as shown in Fig. 14, upon whose surface a narrow horizontal zone is marked off. In radian measure the width of this zone is $l_r d\theta$, θ being the angle of elevation of the zone. The area of this elementary zone is

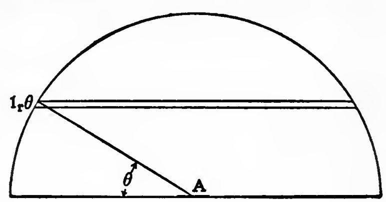


FIG. 14.

$$dA = 2\pi l_r \operatorname{Cos}\theta \cdot l_r d\theta = 2\pi l_r^2 \operatorname{Cos}\theta d\theta.$$

Its value in solid angle units is

$$d\omega = \frac{dA}{l_r^2} = 2\pi \operatorname{Cos}\theta d\theta.$$

The flux emitted within this zone by the diffusing surface is

$$d\phi' = I_\theta d\omega = I_n \operatorname{Sin}\theta \,.\, 2\pi \operatorname{Cos}\theta d\theta,$$

and the total flux emitted by the entire area A throughout the hemisphere is

$$\phi' = \int_0^{\frac{\pi}{2}} 2\pi I_n \operatorname{Sin}\theta \operatorname{Cos}\theta d\theta = \pi I_n;$$

whence

$$I_n = \frac{\phi'}{\pi} = \frac{\phi r}{\pi}.$$

These conclusions may be stated verbally as follows. The quantity of light emitted by a diffusing surface equals its normal intensity times π, and, conversely, the intensity of the light normal to a diffusing surface equals the total flux emitted divided by π.

The illumination received by a point from the light of a diffusing surface at a distance l not less than ten times the maximum apparent dimension of that surface may be found by the law of inverse squares, Lambert's cosine law and the law of the cosine of the angle of incidence as follows. The illumination normal to the beam at the point p, Fig. 15, is

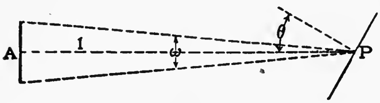


FIG. 15.

$$E_n = \frac{I_n \text{ Cos } \theta}{l^2} = \frac{Ae \text{ Cos } \theta}{l^2}.$$

Since A is small compared to l we may write as the solid angle subtended by A at p the value

$$\omega = \frac{A \text{ Cos } \theta}{l^2},$$

whence the illumination at p normal to the beam may be expressed as

$$E_n = e\omega.$$

If p is a point in a plane whose normal inclines to the beam at the angle θ', we note that the illumination in this plane at p is

$$E = \frac{I_n \text{ Cos } \theta \text{ Cos } \theta'}{l^2} = e\omega \text{ Cos } \theta';$$

that is, the illumination at a point in a plane derived from a diffusing surface is equal to the intrinsic brightness of the surface times the solid angle it subtends at the point times the cosine of the angle of incidence of the beam.

Distribution curves represent by polar coördinates the intensities corresponding to different angles of emission about the vertical and horizontal axes of an illuminant. The curve of vertical distribution of a symmetrical light source unless specially desig-

nated represents the mean of all such distribution curves in all the vertical planes including the axis of the lamp. For strongly asymmetrical light sources curves of vertical distribution are generally shown for special planes. By a somewhat popular fallacy the area included by the vertical distribution curve is sometimes associated with the total flux emitted by the source. As a matter of fact this area is entirely without significance. The curves of Fig. 16 show three possible vertical distributions of a given flux of light.

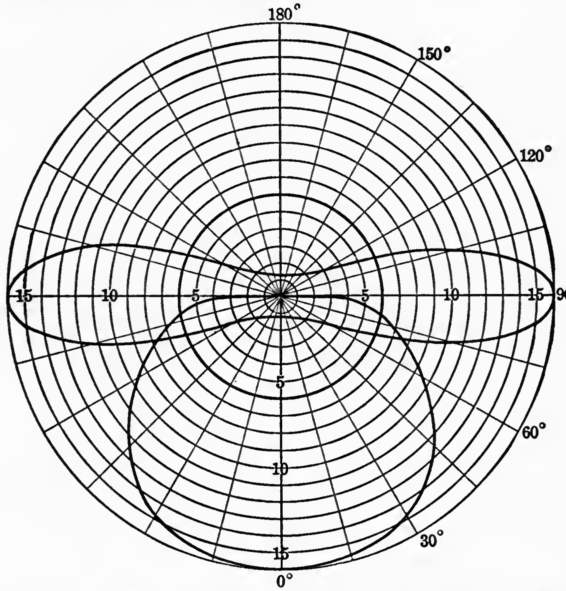


Fig. 16. — Distribution curves of equal quantities of light.

Derivation of mean spherical candle-power and flux of illuminants.—It is frequently necessary to determine from the mean vertical distribution curve of an illuminant its mean spherical intensity or its flux emission within any zonular limits. The principle involved in all of the processes available for this purpose may be derived as follows. Consider the illuminant to be at the center of a spherical surface of radius l_r. Upon this surface is an elementary horizontal zone at an elevation θ above the equator. In radian measure the arc of this zone is $l_r d\theta$, and its area

$$dA = 2\pi r \operatorname{Cos} \theta \cdot l_r d\theta.$$

At the center of the sphere this zone subtends the solid angle

$$d\omega = \frac{2\pi l_r^2 \operatorname{Cos}\theta d\theta}{l_r^2} = 2\pi \operatorname{Cos}\theta d\theta.$$

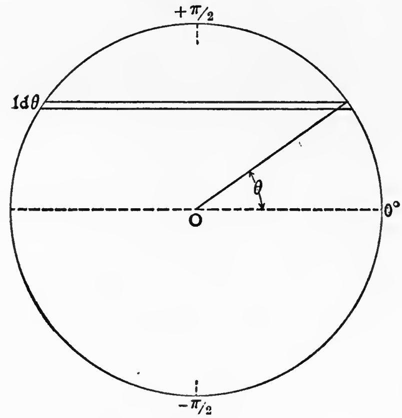


FIG. 17.

Let I_θ be the mean intensity acting upon this zone. The flux emitted within its limits is therefore

$$d\phi = I_\theta d\omega = 2\pi I_\theta \operatorname{Cos}\theta d\theta, \tag{1}$$

and, by integration, the flux emitted within the entire sphere is

$$\phi = \int_0^{\frac{\pi}{2}} 2\pi I_\theta \cos\theta d\theta + \int_{-\frac{\pi}{2}}^{0} 2\pi I_\theta \operatorname{Cos}\theta d\theta, \tag{2}$$

whence the spherical intensity of the illuminant is

$$I_{ms} = \frac{\phi}{4\pi} = \frac{1}{2}\left[\int_0^{\frac{\pi}{2}} I_\theta \cos\theta d\theta + \int_{-\frac{\pi}{2}}^{0} I_\theta \cos\theta d\theta\right]. \tag{3}$$

The integral expressions in the above parenthesis are respectively the mean upper hemispherical and the mean lower hemipherical intensities.

Principle of weighting.—From equation (1) of the above paragraph it is evident that the intensity of an illuminant at an angle θ with the horizontal corresponds to an element of flux proportional to the product of the intensity and the cosine of θ. In all determinations of the flux of an illuminant and of its spherical intensity each radius vector of the polar curve of vertical distribution should be weighted accordingly.

The direct application of equations (2) and (3) above requires the determination of the equation of the polar curve giving the relation between I_θ and θ. The equations of such curves are seldom available, nor is their derivation a simple process. Recourse is generally had to some one of the several approximate numerical or graphical methods which will now be described.

Spherical intensity by weighted average.—Consider the illuminant to be at the center of a spherical surface divided into n horizontal zones of equal width $\frac{\pi l_r}{n}$. If the zones are not too broad and the vertical distribution not too irregular the intensity I_θ at each mid-zone point may be assumed to closely approximate the mean for that zone. The area of each zone equals, to a close approximation, its arc times its mid-zone circumference, or

$$A = \frac{\pi l_r}{n} \cdot 2\,\pi l_r \operatorname{Cos}\theta = \frac{2\pi^2 l_r^2 \operatorname{Cos}\theta}{n}.$$

Each zone subtends at the center a solid angle

$$\omega = \frac{A}{l_r^2} = \frac{2\,\pi^2 \operatorname{Cos}\theta}{n}.$$

Within each zone there is emitted the flux

$$\phi = I_\theta \omega = \frac{2\,\pi^2 I_\theta \operatorname{Cos}\theta}{n}.$$

The total flux within all zones of the sphere is

$$\Sigma\phi = \sum \frac{2\,\pi^2 I_\theta \operatorname{Cos}\theta}{n},$$

and the mean spherical candle-power is derived from this expression as

$$I_{ms} = \frac{\Sigma\phi}{4\,\pi} = \sum \frac{\pi I_\theta \operatorname{Cos}\theta}{2n}.$$

The values of $\frac{\pi \operatorname{Cos}\theta}{2\,n}$ may be readily calculated for a given set of mid-zone points and tabulated as weighting factors. The sum of the products of these factors by the corresponding mid-zone intensities gives the mean spherical candle-power directly. If these factors be applied only to the mid-zone intensities of either the upper or the lower hemisphere the sum of the products so obtained is multiplied by 2 to obtain the mean hemispheri-

cal candle-power. Convenient values of mid-zone points and the corresponding weighting factors are given in Table V.

TABLE V. — WEIGHTING FACTORS FOR VARIOUS MID-ZONE POSITIONS.

Mid-zone Position.	Weighting Factors.	Mid-zone Position.	Weighting Factors.
7° 30′	0.017	97° 30′	0.130
22° 30′	0.050	112° 30′	0.120
37° 30′	0.079	127° 30′	0.104
52° 30′	0.104	142° 30′	0.079
67° 30′	0.120	157° 30′	0.050
82° 30′	0.130	172° 30′	0.018

Table V is intended for use with polar curves divided into zones of 15 deg., the common photometric notation being followed, viz., the 0 deg. position being at the base of the vertical axis and the 180 deg. position at its top.

Spherical intensity by direct average.—This is the simplest of the numerical methods and consists in finding the direct mean of the intensities at different angles such that each corresponds to the mean position of one of n zones of equal area. Consider a spherical surface surrounding the source as a center to be divided into n horizontal zones of equal area. The geometrical theorem that the area of a horizontal zone is proportional to its altitude may be assumed. If the point of bisection of each altitude be projected upon the circumference and a horizontal circle drawn through this point on the sphere this circle bisects the zone in which it is found. If the zones are of sufficient number and the light distribution not too irregular the mean intensity in the direction of each of these

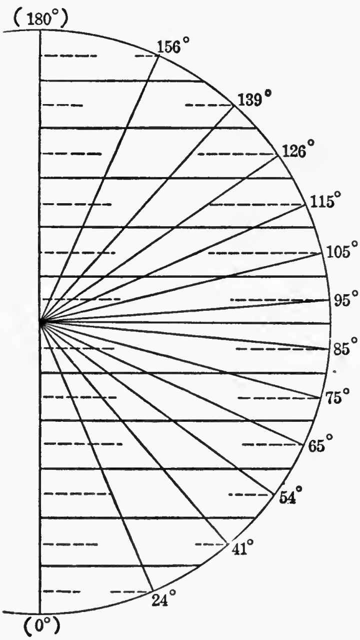


Fig. 18.

bisecting circles may be assumed as the approximate mean for the zone. Each zone has an area of $4\pi l_r^2/n$ and subtends a solid angle of $4\pi/n$. The flux within each zone is

$$\phi = I_\theta \cdot \frac{4\pi}{n},$$

and the total flux within the sphere is

$$\Sigma\phi = \frac{4\pi}{n} \cdot \Sigma I_\theta,$$

$$I_{ms} = \frac{\Sigma I_\theta}{n}.$$

For this method the following positions on the polar curve indicate the most convenient intensities to be averaged:

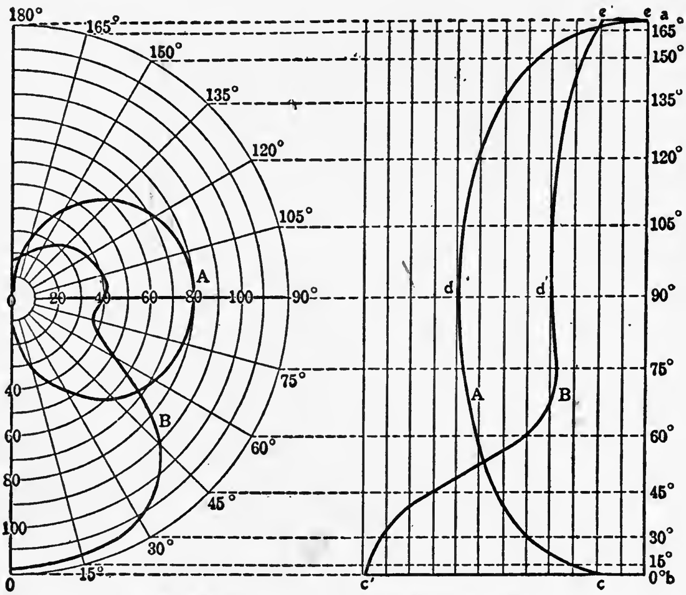
Lower Hemisphere 24, 41, 54, 65, 75, 85 deg.
Upper Hemisphere 95, 105, 115, 126, 139, 156 deg.

The mean spherical intensity is found by averaging the intensities from the polar curve at all the above positions. The mean intensity of either hemisphere may be found by averaging the intensities at the positions specified within its limits. The mean intensity below 60 deg. with the vertical in the lower hemisphere is found by averaging the intensities at the first three of the positions indicated. The flux within this zone is equal to 3.1416 times the mean intensity. In applying this method to the polar curve it is convenient to have at hand a transparent protractor with the radii to be averaged indicated upon it. This protractor may be placed over the polar curve and the readings taken without troublesome interpolation.

Rousseau's diagram[1] performs the weighting and summation of intensities graphically, and its construction and uses may be most conveniently explained by use of an example. Given a curve of mean vertical distribution, as in Fig. 19, the points of intersection of the radii of the polar curve with its outer circle are projected upon a vertical reference line *ab*. Since the area of zone is proportional to its altitude the projection of the entire circle *ab* may be taken to represent the entire sphere of distribution with a value of 4π solid angle units.

[1] Comptes Rendus des Essaies Photometriques à l'Exposition d'Anvers en 1885.

The projection of each zone represents its area, so that the number of solid angle units within each zone may be found by taking four π times the ratio of its intercept to *ab*. On each projection line is laid off from the reference line a length equal to the radius vector of the polar curve at the corresponding angle and the



A - Bare Lamp. B - Lamp and Reflector.

FIG. 19. — Construction of Rousseau's diagram.

points so obtained are connected by a smooth curve *cde*. The area enclosed by this figure represents the weighted mean intensity multiplied by 4π, that is, represents the total flux emitted. Similarly, the area between the limits of any zone represents the flux of lumens within that zone. The mean abscissa of *cde* measured from *ab* represents the mean spherical intensity to the same scale as the polar diagram. Similarly, the mean abscissæ of *cd* and *de* represent respectively the mean intensities of the upper and lower hemispheres. To find the lumens emitted within any zone the ratio of its intercept on *ab* to the length *ab* is multiplied by 4π and by the mean intensity within that zone.

The Kennelly diagram[1] performs the integration of flux and the determination of spherical intensity by a simple process not requiring the use of a planimeter or of other methods of measuring area. Its construction may best be described by an example. In Fig. 20 xyz is the polar curve from which the

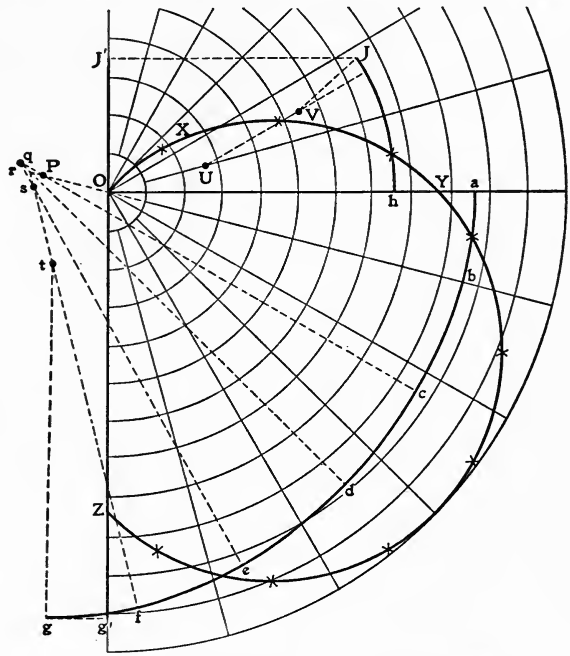


Fig. 20. — Construction of the Kennelly diagram.

derived quantities are to be obtained. This curve is laid off first into a suitable number of equiangular zones, of 15 deg. each, for example, and the mid-zone positions are indicated upon the polar curve. From o as a center the arc ab is drawn through 15 deg., its radius being the radius vector of the polar curve at the first mid-zone point below the horizontal. The line ob is then drawn and upon it is laid off from b a distance bp equal to the radius of the polar curve at the second mid-zone point below the horizontal. With p as a center the arc bc is drawn through 15 deg. and from its lower terminus c is drawn cp. Proceeding

[1] For a full statement of the theory of the Kennelly diagram see Elec. World, March 28, 1908.

as before cq is laid off equal to the radius vector of the next lower mid-zone point and from q as a center the arc cd is drawn through 15 deg. Continuing in this manner an arc of 15 deg. is drawn in succession for each zone of the lower hemisphere, the radius of each being the intensity at the corresponding mid-zone position on the polar curve.

The lower terminus g of the curve so obtained is projected to the point g' on the vertical axis of the polar diagram. Beginning at the horizontal an exactly similar construction is carried out in the upper hemisphere, the curve terminating at the point j, which is projected to j' on the vertical axis of the diagram. The length of the line og' measured to the scale of the polar curve represents the mean intensity of the lower hemisphere. Similarly, the length oj' represents the mean intensity of the upper hemisphere. The arithmetical mean of og' and oj', *i.e.*, one-half the length $g'j'$, represents the mean spherical intensity of the illuminant. The flux within any zone or series of zones may be found by multiplying by 2π the projection on the vertical axis of the corresponding portion of the curves hj and ag.

The principles involved in the above construction may be derived as follows, assuming the geometrical theorem that the area of a zone of a sphere is proportional to its altitude l_a. Consider the light source to be at the center of a hollow sphere of radius l_r and that this sphere is divided into n horizontal zones of equal arc. The total spherical area is therefore proportional to $2\,l_r$. The solid angle subtended by any zone is

$$\omega = \frac{l_a}{2\,l_r} \cdot 4\pi = \frac{2\pi l_a}{l_r}.$$

Assuming the intensity at the mid-zone point I_θ to fairly represent the mean intensity for its zone, the flux within any zone is

$$\phi = I_\theta \omega = \frac{2\pi I_\theta l_a}{l_r},$$

and the mean intensity for either hemisphere

$$I_{mhs} = \frac{\Sigma\phi}{2\pi} = \frac{\Sigma I_\theta l_a}{l_r}.$$

If the radius of the sphere be taken as unity of the candle-power scale of the polar diagram,

$$I_{mhs} = \Sigma I_\theta l_a;$$

that is, the mean intensity of either hemisphere may be represented graphically by a summation of lengths, which represent respectively the mean intensities of the several zones multiplied by the altitudes of the corresponding zones of a sphere of unit radius. It is easily seen that this is what is accomplished by the method of construction described.

The fluxolite diagram[1] devised by Mr. Wohlauer affords a very neat and convenient means of determining the flux within the several zones of distribution and the values of mean spherical

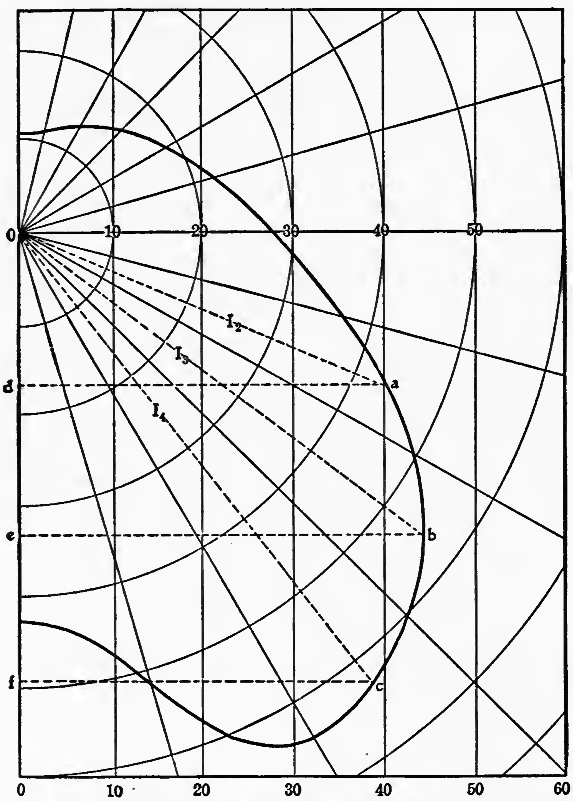


Fig. 21. — The Fluxolite Diagram.

or mean hemispherical intensity derived therefrom. The construction is indicated in Fig. 21. It has been shown that the flux emitted within any zone equals the mean intensity within

[1] Ill. Eng., Vol. III, p. 655.

that zone times the number of solid angle units it subtends. The number of solid angles is proportional to the area of the zone and therefore proportional to its altitude. In Fig. 21 the sphere of distribution is divided into twelve equi-angular zones of 15 deg. each. It may be shown geometrically that the altitude, and hence the area, of each of n equi-angular zones is proportional to the sine of its bisecting angle measured from the vertical axis. Assuming that the mid-zone intensity closely approximates the mean intensity for the zone, the flux within any zone has the value

$$\phi_n = KI_n \operatorname{Sin} \alpha_n,$$

where I_n is the mid-zone intensity, α_n the bisecting angle and K a constant of proportionality. Thus, referring to the diagram,

$$\begin{aligned} \phi_2 &= KI_2 \operatorname{Sin} \angle\, doa = Kad, \\ \phi_3 &= KI_3 \operatorname{Sin} \angle\, eob = Kbe, \\ \phi_4 &= KI_4 \operatorname{Sin} \angle\, foc = Kcf; \end{aligned}$$

that is, the flux within any zone is equal to the horizontal projection of its mid-zone intensity multiplied by a constant. This constant evidently indicates the numerical ratio of the solid angular units within the zone to the sine of its bisecting angle, and may easily be computed for different widths of zone, giving the values in Table VI.

TABLE VI. — VALUES OF K IN $\phi_n = KI_n \sin \alpha_n$.

Width of Zone.	K.	Width of Zone.	K.
5°	0.548	50°	5.3
10°	1.098	55°	5.8
15°	1.64	60°	6.28
20°	2.18	65°	6.75
25°	2.72	70°	7.2
30°	3.25	75°	7.65
35°	3.77	80°	8.1
40°	4.3	85°	8.5
45°	4.8	90°	8.85

The polar curve is laid off with vertical lines spaced equally to the candle-power scale to assist the evaluation of the projections of the several mid-zone intensities. From the summation of the elements of flux within either hemisphere the mean hemispherical candle-power can be derived by dividing the sum by 6.2832, and by dividing the summation of the flux throughout the entire sphere by 12.5664 the mean spherical candle-power is obtained.

CHAPTER VI.

PHOTOMETRIC DEVICES AND THEIR MANIPULATION.

Photometry is the branch of science which deals with the measurement of light and illumination. It is of prime importance to the illuminating engineer, as it is the source of a great bulk of the data at his command.

Subjective limitations.—All successful photometers employ as their mode of measurement the visual comparison of two or more illuminated areas. The accuracy of photometric measurements is therefore subject to the limitations of human vision. Personal peculiarities and deficiencies of eyesight render the results liable to errors for which definite correction cannot be made, due to the lack of an established standard of normal vision. Instruments intended for photometric use should be so devised as to utilize the eye's highest power of discrimination and to protect it from loss of sensitiveness through strain and fatigue. Normal eyes are capable of detecting differences in illumination in bright fields of view as small as a fraction of one per cent. With weak fields the sensitiveness is much reduced. A criterion for accurate photometric measurement requires that the observer be enabled to compare the illumination of two areas to within one per cent.

Objective limitations are due to (1) the assumption of the accuracy of the inverse square law of illumination, (2) the assumption of the accuracy of Lambert's law of the cosine, and (3) the uncertain value of working standards. Fig. 3 shows that the application of the law of inverse squares to sources of finite area may lead to serious error if the reference point is near the source. The diffusely reflecting screens used in photometry often show considerable variation from the cosine law which may give rise to errors. The uncertainty of photometric standards has been previously commented upon. A high degree of consistency is not in itself a proof of accuracy in photometric measurements. By the most refined methods available a final

accuracy of comparison of between 0.5 and 1 per cent can probably be obtained. The valuation of results in primary units, however, depends upon the accuracy of the calibration of the working standard, but the degree of uncertainty may be kept between 1 and 2 per cent.

The simple photometer.—Reduced to its simplest terms a photometer consists of a screen of two diffusing surfaces, illuminated respectively by the two light sources to be compared, and a suitable means of comparing the illumination so obtained. Fig. 22 represents two light sources of respective intensities I_1

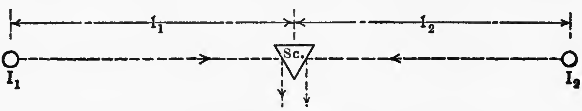


FIG. 22.—Scheme of a simple photometer.

and I_2, the former being known and the latter to be determined. Their respective distances from the photometer screen are l_1 and l_2, and the arrangement is such that both beams have the same angle of incidence θ with the screen. The illuminations of the two sides of the screen are respectively

$$E_1 = \frac{I_1 \operatorname{Cos} \theta}{l_1^2} \quad \text{and} \quad E_2 = \frac{I_2 \operatorname{Cos} \theta}{l_2^2}.$$

By properly adjusting the distances l_1 and l_2 the values of E_1 and E_2 may be made equal with the result

$$\frac{I_1 \operatorname{Cos} \theta}{l_1^2} = \frac{I_2 \operatorname{Cos} \theta}{l_2^2} \quad \text{and} \quad I_2 = \frac{I_1 d_2^2}{l_1^2},$$

which is the fundamental equation of the photometer.

In the above diagram the screen is made wedge-shaped to permit the two sides to be observed simultaneously. Such a photometer is of low sensitiveness unless the edge dividing the two surfaces is made very sharp. Several other devices which present to the observer two or more areas illuminated by the respective light sources are more widely used and the most useful of them will be described in detail.

The Bunsen screen[1] consists of a piece of opaque white paper of fine, even grain and free from glaze, in the center of which is a sharply defined spot rendered translucent by impregnation with

[1] Annalen der Physik und Chemie, Vol. 31, p. 676.

paraffine or stearine. This screen is mounted transversely in a blackened box with apertures to admit the light and to permit the observation of the screen. This box is mounted upon a horizontal bar or track joining the two illuminants under comparison, permitting an easy adjustment of the distances l_1 and l_2. Of the light falling on the opaque areas part is absorbed and the remainder diffusely reflected. Of the light falling upon the spot part is absorbed, part transmitted and part reflected. Unequal illumination of the two sides of the screen results in the transmission of more light from the brighter side than from the other. On the former side the spot appears dim and on the latter side bright in comparison with the remainder of the screen, indicating a lack of balance. Equal illumination of the two sides results in equal transmission in both directions, and the two sides of the screen appear alike if the lights are of similar tint. Screens in which the absorption of light in the spot is the same as that in the ring are known as *disappearance screens*, owing to the disappearance of the spot at the condition of balance. *Contrast screens* have a higher absorption in the spot than in the ring, and indicate the balance condition by the equal contrast and definition of the spot on both sides of the screen. In comparing lights of the same color both types are satisfactory, but with slight color differences the line dividing the spot and the ring cannot be made to disappear and the contrast type is preferable. The contrast type has the added advantage of being less fatiguing to the eye, whose sensitiveness is better maintained when comparing slightly contrasted areas than those equally illuminated.

In the hands of inexperienced and unskilled observers the Bunsen screen yields results as satisfactory as any other. It has the advantages of simplicity, cheapness, ease of manipulation and easy renewal. Its chief disadvantage lies in the difficulty of producing sharp, clear boundary lines between the spot and the ring. It is well-nigh impossible to detect slight inequalities in the illumination of two areas which are indistinctly divided.

The Leeson disk affords an improvement over the Bunsen disk in the latter respect. It employs as a spot a piece of thin translucent paper on both sides of which are pasted opaque pieces with central star-shaped openings whose edges exactly

coincide on the two sides of the screen. Satisfactory screens of this type may be made with either the contrast or the disappearance principle. The Leeson contrast screen is probably the most satisfactory of the simple and inexpensive screens.

To facilitate the determination of the balance it is desirable that both sides of the screen be visible simultaneously. Two upright mirrors set at equal dihedral angles of from 60 to 70 deg. with the screen assist in this process in the Bunsen sight box, as indicated in Fig. 23. Light enters the apertures at the ends, falls upon the screen and is reflected to the observer by the mirrors m_1 and m_2. The sight tube T assists the eyes by screening off external light. Because of inequalities in the reflecting powers of the two halves of the optical system a false balance point might be obtained if but a single setting were made. To permit this effect to be corrected the screen and mirrors are pivoted upon a transverse horizontal axis and may be revolved through 180 deg. so that they are interchanged in the positions. The screen should be balanced in both positions and the mean of the two settings utilized.

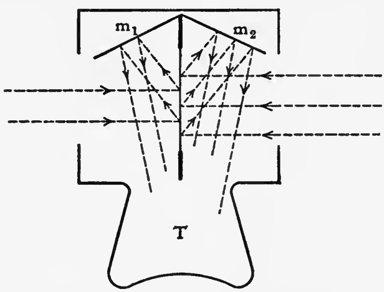


Fig. 23. — Plan of the Bunsen sight box.

When the photometric screen is not of the highest sensitiveness a region will be found about the balance point within which a slight movement of the screen causes no apparent change in the appearance of balance. When this region is approached from one side only the tendency to judge a balance before reaching the middle of the region could scarcely be avoided. Photometric settings should therefore be made by narrowing down the region between two states of the screen equally and oppositely out of balance.

The Lummer-Brodhun photometer presents to the eye two clearly defined elliptical areas as shown in Fig. 24, each illuminated by one of the illuminants under comparison. The screen consists of a disk of white opaque material of high reflecting and diffusing power. Such screens are conveniently prepared by compressing into a circular hole in a metal plate either mag-

nesium oxide, plaster paris or barium sulphate. An accumulation of dirt greatly reduces the reflecting power of such screens and may render the two sides so dissimilar that a considerable change in the balance point is caused by a reversal of the screen. Some screens of recent type employ a specially treated milk glass of matt surface which maintains a high degreee of optical symmetry and admits of occasional cleaning.

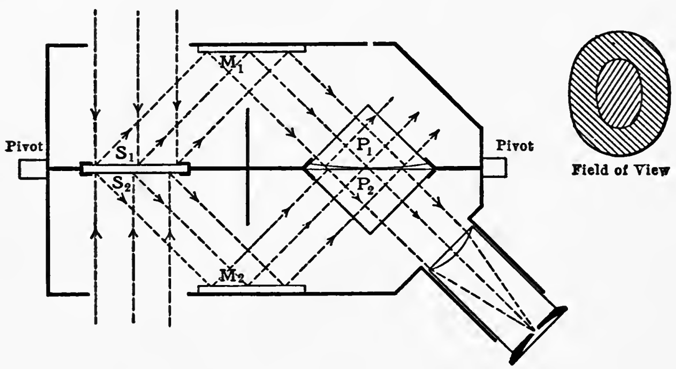


FIG. 24. — Plan of the Lummer-Brodhun photometer.

The plan of the Lummer-Brodhun sight box is shown in Fig. 24. Light from the lamps compared falls upon the diffusing surfaces of the screen S_1 and S_2 along the paths indicated. Mirrors M_1 and M_2 reflect the light of S_1 and S_2 to the totally reflecting prisms P_1 and P_2. These prisms have their hypotenusal faces in contact in a plane coincident with the central plane of the screen. Part of the face of P_1 is ground away, leaving an elliptical area in contact with P_2. Of the light which enters P_1 from M_1 that which falls upon the area of contact passes through into the eyepiece and the remainder is turned aside by total reflection. P_2 reflects to the eyepiece the light which falls upon its outer portion, but that which meets the area of contact passes through and is absorbed in the blackened walls of the box. In the field of view the inner ellipse is thus illuminated by light from S_1 and the outer ellipse by light from S_2. If the face of P_1 is ground with care the dividing line between the two ellipses may be made very sharp. With the field of view uniformly illuminated the boundary line disappears if the lights compared are of the same tint. If not, the balance must be determined from

the appearance of equal brightness. This fact virtually limits the use of the instrument to the comparison of similarly tinted lights. In sight boxes of the best construction the mirrors M_1 and M_2 are replaced by totally reflecting prisms to secure greater symmetry and permanence of reflecting power.

In comparison with the Bunsen screen, in setting which the observer compares two areas somewhat indefinitely divided, the advantage is seen to lie with the Lummer-Brodhun type. The latter instrument, however, is monocular and requires the comparison of two equally illuminated areas, conditions which tend to rapid fatigue and loss of sensitiveness in the eye. The satisfactory use of the Lummer-Brodhun photometer requires that all parts be clean and in accurate adjustment.

The Lummer-Brodhun contrast photometer employs an optical scheme similar in all respects to that above described with the

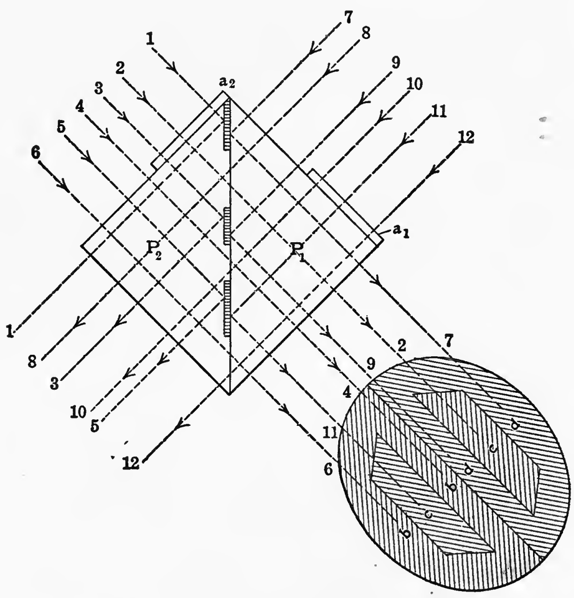


Fig. 25. — Prisms and field of Lummer-Brodhun contrast photometer.

exception of the prisms. Fig. 25 shows a horizontal section of the prisms and the elevation of the field of view at a state of balance. On the outer face of P_1 and P_2 are fastened similar plates of glass a_1 and a_2, each covering exactly one half of the

face of the prism. Tracing the paths of the beams as indicated, it is seen that b appears illuminated by light from S_2 which has not passed through a_2; c appears illuminated by light from S_1 which has been somewhat dimmed by absorption in passing through a_1; e is illuminated by light from S_2 dimmed in passing through a_2; and d is illuminated by the undimmed light from S_1. c and d are lighted from the same source, though c is somewhat dimmer. b and e are lighted from the other source, with e dimmer than b. At a state of balance the central portions c and e appear equally contrasted with the surrounding semi-ellipses, as indicated in the elevation of the field of view.

This instrument embodies the highest development of the contrast principle and yields an excellent degree of sensitiveness with lights of similar tint. The contrast principle is distinctively advantageous with moderate differences in color, but the difficulty of setting increases rapidly with the color divergence. For general use this photometer affords the most sensitive and reliable device at the disposal of the skilled observer. Its monocular nature and its great sensitiveness to flicker constitute its chief faults.

Recent investigations indicate that the most satisfactory photometric measurements of illuminants differing in color from the prevailing standards can be made by passing the beam into the Lummer-Brodhun photometer through a tinted glass window by whose selective absorption the color is equalized with that of the standard. Correction is made for the absorption in the window by dividing the result by the screen's coefficient of transmission. A series of properly graded screens whose transmission coefficients have been accurately standardized forms a valuable adjunct to the equipment of a photometric laboratory.

Flicker photometers[1] are designed for the comparison of illuminants of widely divergent color values. The principle involved was first worked out by Rood. A field of view alternately illuminated by two sources displays a flickering appearance which may be due to difference in color or to difference in intensity. If a certain low frequency of alternation be exceeded the color flicker disappears as a result of optical blending. The intensity flicker, however, persists to a high frequency unless the two illuminations are equalized. The speed of alternation employed

[1] Amer. Jour. of Sci., Vol. 46, p. 173.

in setting the screen for a photometric balance should be that yielding the highest sensitiveness for the particular illumination and color divergence of the field encountered.

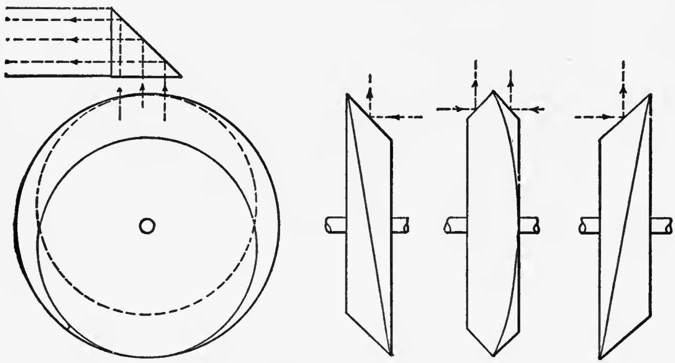


Fig. 26. — Simmance-Abady screen in various stages of revolution.

The well-known **Simmance-Abady screen** consists of a thick disk of plaster paris molded to form a double conoid of revolution. The disk is turned by a clock-work mechanism about its axis. Above the top of the disk is a sight tube, in which a mirror or a totally reflecting prism presents to the eye a field of view whose illumination from each source varies continuously from 0 to 100 per cent of the whole. A speed regulator is provided to permit adjustment of the frequency of alternation.

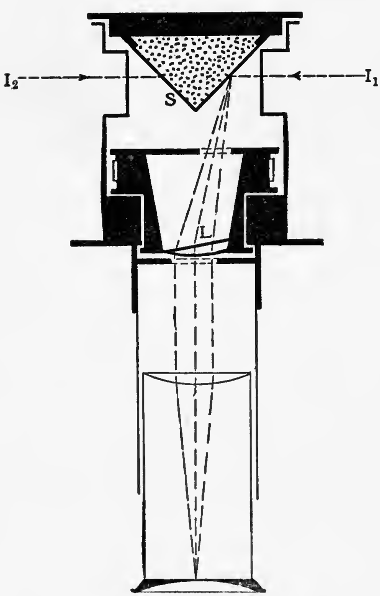


Fig. 27. — Flicker photometer by Franz Schmidt & Haensch.

An admirable flicker screen made by Schmidt & Haensch has a wedge-shaped stationary screen of plaster paris S (Fig. 27) before which is revolved a lens L, the axis of revolution being inclined to the optical axis so that the lens alternately

focuses upon the two faces of the wedge when viewed from the eyepiece.

The mounting of photometers.—The photometric screens above described are generally employed in connection with a track or bar supporting carriages for the lamps and the screen. Such a track should be straight and level and should be firmly supported. Its length should preferably not be less than 10 feet or 3 meters. For measurements of illuminants of large area a much longer track is desirable. Photometer bars for the testing of gas are generally supported at the ends by blackened tables upon one of which is mounted the gas burner with its accessory meter, pressure regulator and regulating cock and on the other either a candle balance or some type of flame standard lamp. Similar blackened tables are a convenience in the testing of electric lamps, furnishing a convenient support for voltmeters, ammeters, regulating rheostats, switches, etc., for which they are often permanently wired. A fixed scale of equal divisions is generally attached to the track to permit the distances from the screen to the lamps to be conveniently read. A ratio scale indicating the ratio of the intensities corresponding to various balance positions of the screen is often found to be a convenience. A clamping rod by which one of the lamp carriages and the screen carriage may be firmly coupled together is convenient for substitution methods of comparison.

Behind each lamp should be placed a dead-black surface to prevent the reflection of light along the track. Between the lamps and the screen should be placed diaphragms of dead-black surface. Their central apertures should coincide with the photometric axis and permit the unobstructed passage of the direct rays to the screen. They should occlude all foreign light from the screen and protect the eyes of the observer from all direct beams. It is customary to mount the photometer in a room whose walls, ceilings and all possible contents are painted dead black and from which all external light is carefully excluded. Such precautions are advisable, but not indispensable.[1] The walls of the room may be white, and well-diffused light may be admitted to the room if the requisite precautions are observed in disposing the diaphragms along the track. The proper arrangement is illustrated in Fig. 28. Back of each lamp is placed

[1] Bull. No. 3, U. S. Bur. of Stand., p. 417.

a dead-black screen. Between each lamp and the sight box is a series of diaphragms of graded apertures so placed as to cut off every ray of light from the screen save that from the lamps

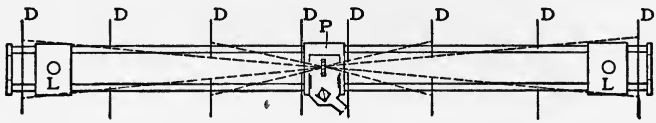


Fig. 28. — Arrangement for light room photometry.

under test. To ascertain whether these conditions are amply fulfilled it is sufficient to make certain that no part of the screen can be seen from any position except by sighting down the photometric axis. This test should be made with the screen strongly illuminated. Photometric rooms in which tests are conducted with open-flame illuminants or standards should be well ventilated without the formation of strong air currents, as the vitiation of the air has a marked effect on the luminosity of flames, and drafts result in an annoying flicker.

Manipulation.—The plan of manipulation most frequently followed consists in mounting the lamps in fixed positions at the ends of the track and bringing the screen to a balance by narrowing down the space surrounding the balance point, whereupon the screen is reversed and the operation of balancing repeated, the mean of the two settings being taken as the true balance point. To such an operation the usual photometric equation applies:

$$I_2 = \frac{I_1 l_2^2}{l_1^2}.$$

In cases where a large number of similar observations are to be taken with incandescent electric lamps a *substitution method* may be employed to advantage. A fully seasoned incandescent lamp is mounted upon one of the lamp carriages and is maintained at a constant potential. Its carriage and that of the screen are firmly linked together by a clamping rod of suitable length. The intensity of the comparison lamp need not be known but its constancy must be reliable. This lamp furnishes a constant illumination on the adjacent side of the screen. A standard lamp is then mounted at the other end of the track and adjusted

to its standard intensity. The screen carrying the comparison lamp at a fixed distance is moved to the balance point and its distance from the standard lamp noted without reversal of the screen. Let l_s denote this distance. The standard lamp is replaced by each of the lamps to be tested in turn and a similar observation made for each, the setting being l_x. The results of the test are computed by the equation

$$I_x = \frac{I_s l_x^2}{l_s^2}.$$

When a long series of observations is taken it is advisable to check the constancy of the comparison lamp against the standard from time to time. This method obviates the reversal of the screen, since the lamps tested and the standard are placed on the same side of the screen. The standard is subjected to a minimum of handling and deterioration.

Tests of the illuminating power of gas are made by comparing the intensity of the gas flame of a standard argand burner consuming five cubic feet of gas per hour with the intensity of a standard pentane lamp or of a pair of standard candles. As the flames and the standard are assumed to be equally affected by atmospheric deviations from normal, corrections for such conditions are avoided. A standard pentane lamp is assumed to give its normal intensity with the flame adjusted to the height of the index. When candles are employed the intensity of the pair is assumed to vary directly with the rate of sperm consumption if within 5 per cent of the standard rate of 120 grains per hour per candle. The candles are mounted upon a candle balance, carefully trimmed, the ends of the wicks bent at right angles and given a preliminary burning sufficient to form good cups and insure a uniform rate of burning. With all in readiness the weights are adjusted and the time of exact balance observed. A 40-grain weight is then removed and the interval elapsing before the scale again balances is carefully determined. With the correct rate of sperm consumption this interval should be ten minutes, but the test is accepted if the period falls between 9.5 and 10.5 minutes, proportionate correction being made in the luminous intensity of the candles.

Ten photometric settings are taken in this period, five of which are made with the screen reversed from its original position.

The flow of gas is read from an indicating meter at the beginning and at the end of the test, and should closely agree with the standard rate of 5 cubic feet per hour. The observed rate must be corrected to the equivalent value at a gas temperature of 60 deg. fahr. and an atmospheric pressure of 30 inches of mercury. Table XX of the appendix is intended to assist in this correction. When a ten-candle pentane lamp is employed the results may be computed as follows: —

$$\text{I.P.} = \frac{10 \times k \times 5}{I \times N},$$

where k is the ratio of intensities indicated by the photometric setting, I the observed rate of flow of gas and N the tabular number from Table XX corresponding to the observed barometric pressure and gas temperature. With candles employed as standards the results are

$$\text{I.P.} = \frac{2 \times 10 \times k \times 5}{T \times I \times N},$$

where T is the interval required for the consumption of 40 grains and k, I and N have the same significance as above.

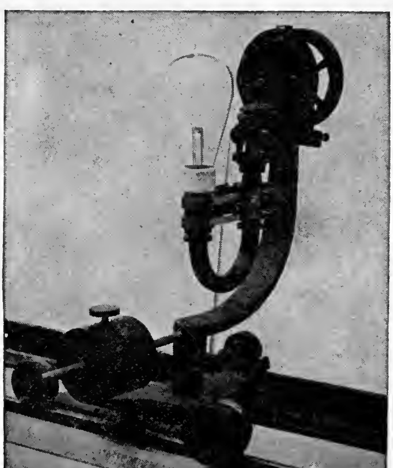


Fig. 29. — Universal rotating socket.

Photometric accessories.—The universal rotating socket, of which Fig. 29 is an illustration, permits the determination of the intensity of an incandescent electric lamp in any direction and of

the mean intensity at any angle of inclination with its axis. Divided circular scales are provided to indicate the angular position of the lamp. A pulley and shaft communicating with the socket permit the lamp to be rotated about its axis at any inclination by a small motor or a hand rotator. The speed of rotation should be sufficient to overcome the annoying flicker caused by unevenness in the light distribution, but should not be so great as to distort the filament by centrifugal force.

In the photometry of arcs, Nernst lamps, gas lamps, etc., it is necessary to maintain the lamp in a vertical position. The intensity at any other than the horizontal direction can be measured only by the aid of an accessory device to select the beam at the desired angle and direct it toward the photometer screen. One device employed for this purpose has three mirrors arranged as indicated in Fig. 30. The device may be turned as a unit about

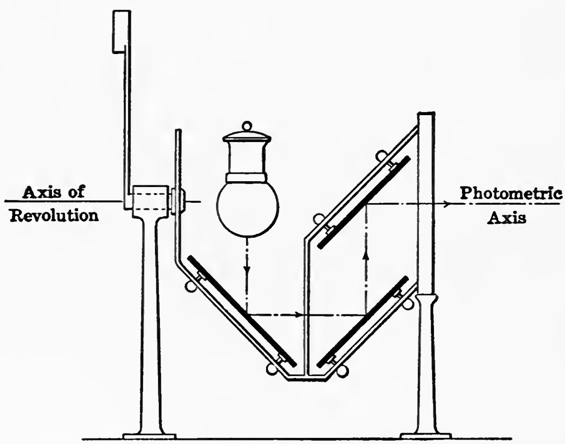


FIG. 30. — Three-mirror photometric selector.

a horizontal shaft so as to reflect toward the screen the beam emitted by the lamp at any desired angle with the vertical axis.

Another device employed for this purpose is illustrated in Fig. 31. The lamp is suspended from a pivoted arm at such a distance that its luminous center is in the axis of revolution when the arm is in its upright position. At a distance below this axis equal to the length of the suspension arm is a mirror set at an angle of 45 deg. with the photometric axis, about which the

mirror may be revolved by a worm gear. The gear communicates the same rate of revolution to the suspension arm, causing the lamp to describe a circle about the mirror, which always reflects the incident beam along the photometric axis. In this case the length of the photometer is equal to the radius of the lamp's revolution plus the distance from the center of the mirror to the standard lamp at the further end of the track.

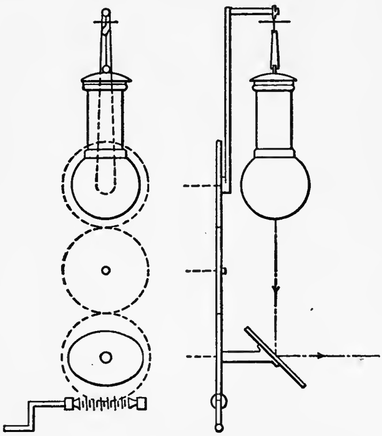


Fig. 31. — Single-mirror selector.

Observations taken by either of the two above mentioned selectors require correction for the absorption of the mirrors. The coefficient of reflection may be determined by measuring the apparent intensity of a previously calibrated lamp by means of the device. The ratio of the apparent intensity to the true intensity gives the coefficient of reflection. In the use of both of the above devices care must be taken to occlude from the screen the direct beams of the lamp.

Great difficulty and uncertainty are introduced into the photometry of arcs by the tendency of the arc to wander about the ends of the electrodes. This renders the light in any direction so variable that a long series of measurements must be made to arrive at an average result. A method of reducing this difficulty was suggested by Matthews, who employed two revolving mirrors, symmetrically placed on arms which are revolved in opposite directions about the horizontal axis of the lamp by means of a crank and gear. The direct rays are occluded from the screen, which receives light from the two sides of the lamp by the aid of the mirrors. These are set to focus upon the screen, which remains in a fixed position. The illumination of the screen when balanced by a standard lamp on the opposite side is

$$E = \frac{I_1 r_1 \operatorname{Cos} \theta}{l^2} + \frac{I_2 r_2 \operatorname{Cos} \theta}{l^2} = \frac{I_s}{l_s^2};$$

whence the mean intensity of the beams measured becomes

$$\frac{I_1 + I_2}{2} = \frac{I_s}{l_s^2} \cdot \frac{l^2}{r \operatorname{Cos} \theta} = \frac{I_s}{l_s^2} \cdot K,$$

where r_1 and r_2 are the respective reflection coefficients of the mirrors and r their combined value. K may be computed from the above values or may be experimentally determined by determining the ratio of the true intensity to the apparent intensity of a standard lamp by means of the device.

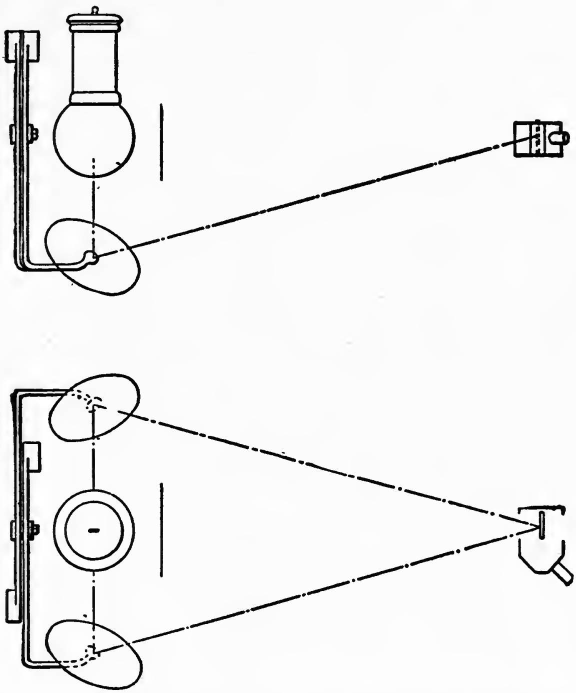


Fig. 32. — Matthews double-mirror selector for arc photometry.

The sectored disk is employed to reduce the intensity of a beam by a given amount without in any way altering the quality of the light. It consists of a rotating disk with radial slots whose angular aperture may be varied within suitable limits and is placed in the path of the beam. By Talbot's law the ratio of the angular opening to 360 deg. equals the ratio of the apparent intensity to the true intensity of the beam intercepted.

A storage battery of ample capacity should be employed wherever possible as the source of supply in the photometric testing of electric lamps because of the constancy of its pressure. When a battery is not available the lamps compared should,

if possible, be operated from the same circuit so that the effects of pressure variations may be fairly equalized. A gas holder of ample capacity has a value in gas testing analogous to that of the storage battery. When the gas is drawn from the supply pipes a sufficient amount should be drawn off before testing to thoroughly purge the pipes from stale gas.

Non-visual photometers. Reference should be made to the photometric utility of the *selenium screen*, the *bolometer* and the *thermopile*. Selenium undergoes a change of electrical conductivity upon exposure to light, but its response to different wave-lengths does not agree with that of the retina, being more favorable to the blue end of the spectrum. The slow adjustment of its resistance to a given illumination and its hysteretic behavior render its manipulation difficult.

The bolometer, which consists of a thin iron wire coated with carbon, becomes heated upon exposure to radiation, the intensity of which may be measured by determining the change of resistance. Its indications are strictly limited to total radiation without regard to the luminous equivalent. The thermopile like the bolometer gives indications proportional to total radiation rather than to luminous intensity.

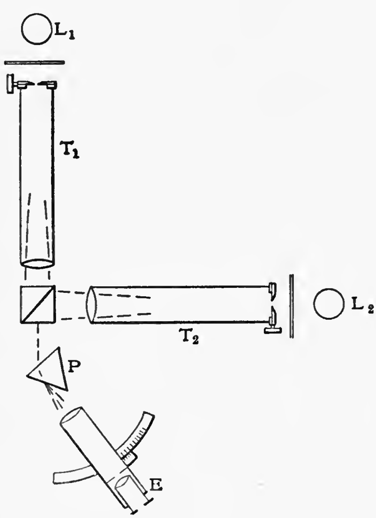


Fig. 33. — Scheme of a spectrophotometer.

These instruments are of value in photometry when a long series of observations are to be made with light of a definite quality. In such a case the indications may be evaluated in photometric units by a proper calibration.

The spectrophotometer is a device for the comparison of single color components in the spectra of two illuminants. The principle of such devices may be explained by reference to Fig. 33. T_1 and T_2 are collimator tubes with adjustable slits in their exposed ends. Before these slits are placed the illuminants L_1 and L_2, with plates

of milk glass interposed to diffuse the light. The rays from the collimators fall upon a Lummer-Brodhun cube, pass from it to a diffracting prism and are opened out into superposed spectra. The observing telescope E may be turned in an arc about P as a center to the particular position in the spectrum at which the comparison is to be made. The photometric balance is secured by adjusting the slit widths, the two intensities being inversely proportional to the respective slit widths. A circular scale indicates the wave-length of the spectrum at which the comparison is made.

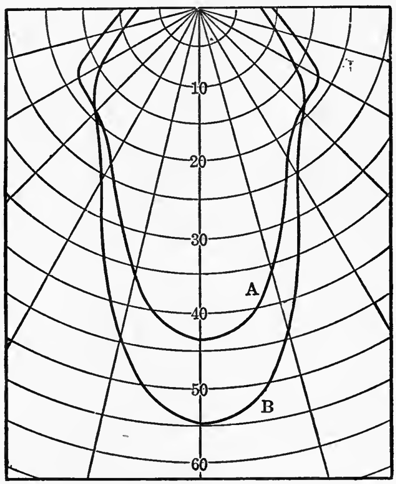
The Ives colorimeter[1] is a device for the measurement of color in terms of the three elementary colors, red, green and blue. "It consists essentially of an oblong box, at one end of which are placed four slits, one clear, the other three furnished, respectively, with a red, a green and a blue color screen. By means of levers the openings of the three colored slits may be altered to read by scales from zero to one hundred. Within the instrument is a wheel of lenses which when rotated rapidly by a small motor causes the three colors to pass across the field of vision of the eyepiece, thus mixing them by persistence of vision. The optical arrangements are such that one observes a divided field, one half consisting of the mixture of the three colors, the other of the color to be matched, as viewed through the clear slit. For ordinary use a white surface reflecting the light of the sky serves as a standard white. To make a measurement, the three levers are opened until white is matched and the scales are adjusted to read 100 for each color; then any color matched by moving the three levers can be read off in terms of the red, green and blue used to match white."

This instrument is equally applicable to the analysis of the light from various sources and to the determination of the effects of different illuminants upon the appearance and color value of fabrics. Results of color analyses of various modern light sources made by the colorimeter are recorded in Chapter IV.

Reflectors and units of large size lead to difficulty in photometric measurements because of their concentrating effects upon the beams and their large luminous area. An extreme case of the former difficulty is found in the case of a parabolic reflector which concentrates all its light in a single direction and would

[1] Trans. Ill. Eng. Soc. Vol. III, p. 627.

therefore, theoretically, at least, produce the same illumination of a photometric screen whatever be their distance apart. The practical result of the concentration of the beams and the large area of the light source in the case of reflectors and large units is illustrated in Fig. 34, which shows the two distribution curves



A - Distance from Screen = 4 ft.
B - " " " =10 ft.

FIG. 34. — Distribution curves obtained from the same reflector at different distances from the photometric screen.

obtained from the same reflector when the photometric screen was placed at different distances. To avoid such discrepancies and insure that all curves may be derived in the same manner it is recommended that a standard distance of ten feet be maintained between the source and the screen in all photometric measurements of reflectors and large units. When this plan is followed, however, the distribution curves must be regarded as approximate in computing the illumination produced at different distances from the source.

CHAPTER VII.

PORTABLE PHOTOMETERS AND ILLUMINOMETERS.

THE apparatus described in the preceding chapter is adapted only to permanent mounting in a photometer room. The measurement of illumination and the testing of illuminants in place impose the essential conditions of portability, adaptation to use in any position, freedom from all dependence upon dark-room conditions and a good degree of sensibility over a very wide range of intensities.

The Weber photometer is a widely known representative of this class and its general principles have been copied with many modifications in apparatus of later design. Structurally considered it consists of two cylindrical tubes of blackened interior (Fig. 35),

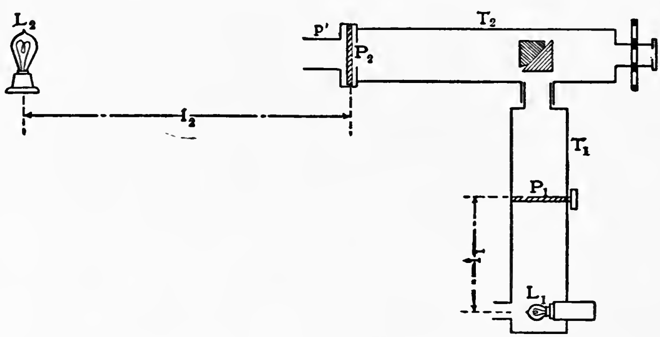


FIG. 35. — The Weber photometer.

one of which T_1 is firmly clamped to an upright standard, and the other T_2 is attached to one end of T_1 by a friction sleeve, which permits T_2 to be turned to any desired angle in a vertical plane. The instrument as a whole may be turned to any desired angle about its standard as an axis, thus permitting the pointing of T_2 at any angle. Optically considered the Weber instrument is seen to be a modification of the Lummer-Brodhun photometer, the essential change being the substitution for the opaque screen

of two glass diffusing plates P_1 and P_2 placed between the prisms and the lamps to be compared. In a suitable chamber at the end of the lamp tube is mounted a comparison lamp L_1, preferably a miniature tantalum or tungsten filament lamp operated by a storage battery. This lamp should be well seasoned before use to insure its constancy. The original design contemplated the use of a small-flame lamp burning benzine, but the tendency to smoke and to vary in intensity renders its manipulation tedious and its accuracy questionable.

The diffusion plate P_1 is movable along the axis of the tube by means of an external milled head carrying an index to indicate its position. At P_2 any one or more of a number of plates of different transmission coefficients may be used interchangeably. A beam of intensity I_2 from the lamp to be tested falls upon P_2, producing an illumination on its inner side of the value

$$E_2 = \frac{I_2 t_2}{l_2^2},$$

t_2 being the transmission coefficient of the plate P_2. Similarly the illumination of P_1 as presented to the prisms is

$$E_1 = \frac{I_1 t_1}{l_1^2}.$$

By a proper adjustment of the distances l_1 and l_2 and of the transmission coefficient t_2 a photometric balance may be obtained, indicating the equality of E_1 and E_2, whence

$$\frac{I_1 t_1}{l_1^2} = \frac{I_2 t_2}{l_2^2},$$

and the candle-power to be measured is found to be

$$I_2 = \frac{I_1 l_2^2}{l_1^2} \cdot \frac{t_1}{t_2}.$$

The ratio of the transmission coefficients t_1/t_2 is a constant for a given pair of plates and may be readily determined by using lamps of known intensity as L_1 and L_2 at known distances l_1 and l_2, or the constant may be made to include the value I_1 if its constancy can be relied upon. The range of transmission coefficients afforded by the several plates usually provided for use at P_2 permits the observer to adapt the photometer to a wide range of candle-power and illumination measurement.

The eyepiece of the instrument is provided with a metal slide having three apertures, one open, one of red glass and the other of green glass. Lights of similar tint may be compared through the first of these, but where the color difference renders the balance uncertain the comparison may be made through the two colored glasses successively and the results combined by the equation

$$I_2 = I_r k,$$

I_r being the apparent intensity measured through the red glass and k a value depending upon the ratio of the apparent intensity I_g as seen by the green plate to I_r and upon the particular glasses used as P_1 and P_2. A table of values of k corresponding to various values of I_g/I_r and t_1/t_2 should be secured with the instrument or may be experimentally determined.[1]

The Weber photometer may be conveniently used to measure the intensity and light distribution of arc lamps in connection with a mast or frame pivoted at one end so as to revolve in a vertical plane and carry the lamp suspended at the other end in a circle about the photometer, as shown in Fig. 36.

Two methods are available by which the Weber photometer may be utilized to measure illumination. One method employs a special test plate mounted as a cap upon the end of the sighting tube at p'. The instrument is then placed so that this plate occupies the position whose intensity of illumination is to be measured. The balance is secured in the usual manner, the totally reflecting prism at the eyepiece being used to assist the sighting when desired. The scale of the instrument should be calibrated by the aid of a standard lamp placed at suitable distances from the test plate to produce upon it known values of illumination. Wherever it can be applied with convenience this method is preferable, as it does not obstruct any of the light which should fall on the test plane.

The above method is unsuited, however, to the measurement of the illumination of surfaces with which the test plate cannot be made to coincide, such as the tops of tables and counters. The alternate method must then be employed. A white diffusing screen of good diffusing quality is placed in the position to be tested and is observed through the sighting tube T_2, the glass plate P_2 being removed unless it is required to reduce the intensity

[1] Palaz and Patterson, Industrial Photometry, p. 85.

of the field. The distance of the screen from the end of the tube and the angle between them are inconsequential, provided the screen intercepts the entire cone of light entering the tube and closely agrees with the cosine law of diffusion. Calibration is

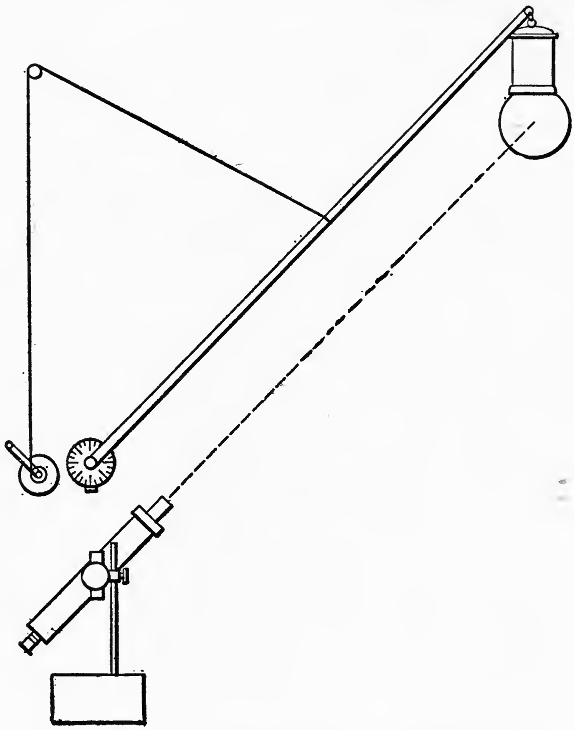


Fig. 36. Mast arrangement for arc lamp photometry.

accomplished by the aid of a standard lamp at suitable distances from the screen. Serious error may arise in the use of this method by the obstruction of light by the instrument and observer and because of imperfections in the diffusing power of the screen.

A modified Weber photometer employing a diffusely reflecting test plate is shown diagrammatically in Fig. 37. The test plate P is mounted upon a pivoted arm in such a manner as to permit its adjustment to any desired inclination. The illumination of this plate is compared with that of the diffusing plate G by means of a Lummer-Brodhun train. The balance is obtained by

adjusting the position of the comparison lamp *L*. The obstruction of light by the observer and the instrument is a serious disadvantage of this type of instrument.

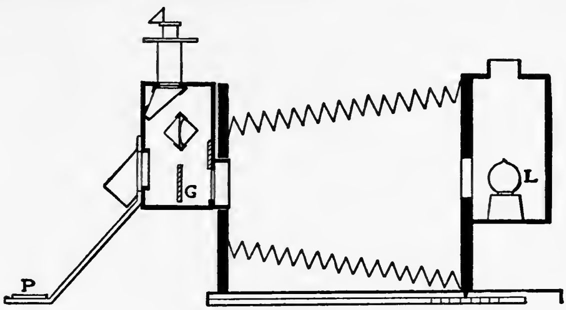


Fig. 37. — Modified Weber illuminometer.

The Sharp-Millar photometer is designed to apply the principles of the Weber instrument to a range of measurements so wide as to merit the name of a universal instrument. A compartment at one end of a box of blackened interior contains a Lummer-Brodhun prism set, which may be observed through an eyepiece *E* on the side of the box. The adjacent end of the box

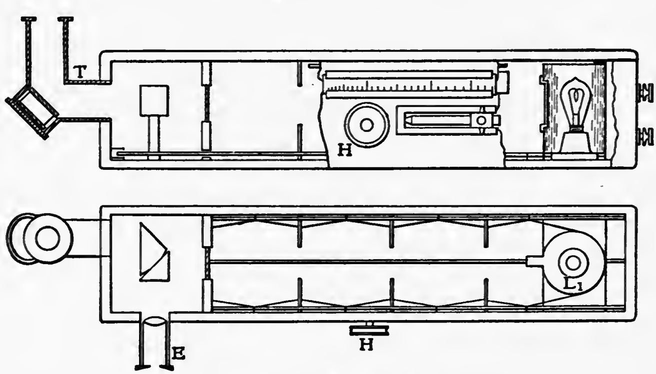


Fig. 38. — Sharp-Millar photometer.

carries a collar, upon which an elbow tube *T* may be turned so as to expose its end at any desired inclination. Upon this end may be fitted a diffusing cap of special milk glass or an open diaphragm. At the elbow of the tube is a circular reversible plate, one side of which is a mirror for use with the diffusing test

plate in the measurement of illumination. The other side is a white matte surface for use in connection with the diaphragm above referred to for measurements of candle-power. The end of the prism compartment opposite the elbow tube contains a milk-glass window illuminated by the comparison lamp L_1 at the further end of the box. This lamp is mounted upon a carriage which may be drawn along the interior of the box by turning the knurled head H. Between the lamp and the window is a series of diaphragms to screen from the window all but the direct beams of the lamp. The photometric balance is secured by drawing the comparison lamp along the interior of the box. When a balance is obtained the reading is taken by exposing a translucent scale on the side of the box by raising a shutter. This scale is made direct reading for comparison lamps of definite intensity.

For measurements of illumination the elbow tube is fitted with its diffusing cap and its mirrored elbow plate. If the illumination is moderate in intensity it may be read direct from the scale. If intense illumination is measured a smoked-glass absorbing plate is required between the elbow tube and the prisms to equalize the two fields and bring the balance point within the limits of the scale. The scale readings must then be multiplied by the reciprocal of the transmission coefficient of this plate. For measurements of weak illumination the absorbing plate is required between the milk-glass window and the prism, and the readings of the scale are multiplied by the transmission coefficient of this plate. The instrument is provided with two such plates, which are so mounted that either may be turned by a milled head to a position in front of the elbow tube or before the window or may be turned entirely out of the path of the beams. Convenient values for the transmission coefficients of these plates are 0.01 and 0.10 respectively, giving the instrument a range of from 0.004 foot-candles to 2000 foot-candles.

The Marshall illuminometer, whose arrangement is shown in the diagram of Fig. 39, operates upon the principle of balancing the illumination of the exposed side of a Bunsen screen by light from a miniature incandescent lamp in the enclosure beneath. Balance is obtained by adjusting the voltage of the lamp. By measuring its resistance upon the slide wire of a wheatstone bridge at this voltage the intensity of illumination is obtained from a previously determined calibration of the slide wire. The sensitiveness of

the device is low, color variations introduced by varying the voltage of the comparison lamp add to the difficulty of its

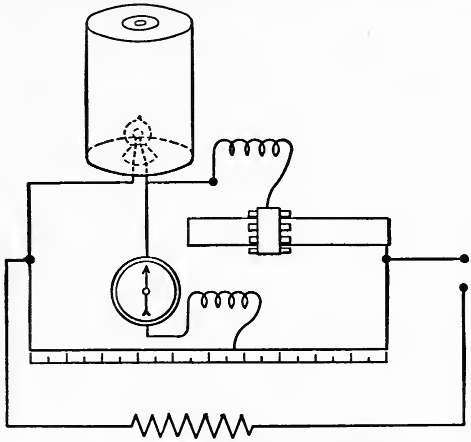


Fig. 39. — Marshall illuminometer.

manipulation, and the obstruction of light by the observer is a cause of serious error.

The Preece-Trotter photometer involves some valuable features as well as several disadvantages. The body of the instrument

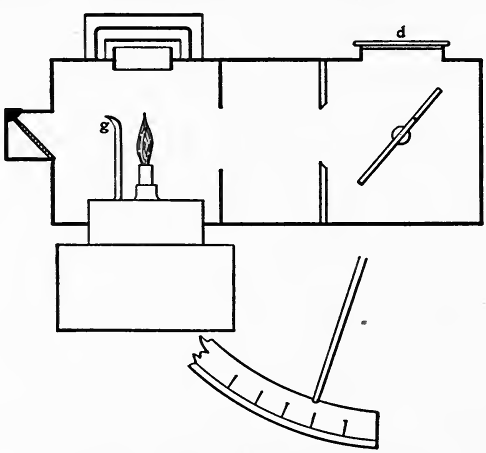


Fig. 40. — Preece-Trotter photometer.

consists of a cylindrical tube with closed ends supported with its axis horizontal. Projecting up through the bottom of one end of the tube is the burner of an amyl-acetate lamp with a

point gage g to indicate the correct flame height. At the other end of the tube is an inclined bristol board, pivoted horizontally and transversely to the tube. Above this screen is a white disk d with a slot through which the inclined bristol board may be observed. The instrument is balanced by equalizing the apparent illumination of this screen with that of a circular disk by changing the inclination of the screen. An external pointer attached to the screen moves about a circular scale which is calibrated directly in foot-candles. The sensitiveness is low and the operation of the instrument involves the occlusion of some light which should reach the test plane.

Reading photometers have been employed to some extent in the measurement of street illumination. An example will suffice to indicate the principle and method of their operation. Fig. 41 is a sectional sketch of a box of blackened interior fitted with a sight tube S and a light tube L. On the rear side of the box is a white card C bearing characters in type of different degrees of boldness. The setting is made by finding the distance from the illuminant at which the eye first becomes unable to distinguish one of the sets of characters when lighted by the beam of the lamp, the vanishing value of illumination for each set of characters having been determined by previous calibration.

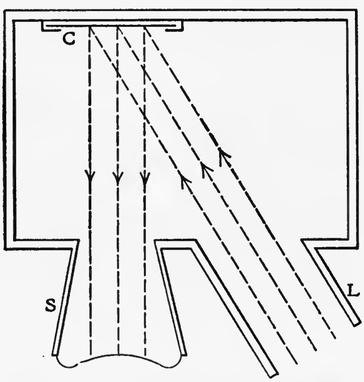


Fig. 41. — Section of a reading photometer.

It is obvious that such a method of measurement suffices only for the crudest of comparisons. Its indications are based upon the properties of the light that make for visual acuity rather than the true intensity. In its use the subjective factor is overemphasized, rendering the observations of different observers liable to great inconsistency.

The science of illumination measurement has been regarded with deserved suspicion by many because of its greater difficulty and numerous sources of error as compared with the photometry of light sources. If serious attention is to be given the

often recurring suggestion that the customers of lighting companies be charged according to the actual illumination secured and that street lighting be rated and paid for on a mean or a minimum illumination basis, reliable methods of measurement are indispensable. A satisfactory illuminometer must possess the following essential characteristics: — (1) a sensitive photometric device capable of accurate settings in a weakly illuminated field when necessary; (2) a reliable comparison lamp, accurately rated and of great constancy; (3) high accuracy over a wide range of intensities; (4) a test plane whose surface is free from selective reflection and closely accords with the cosine law of diffusion; and (5) the position of the test plane and the observing device such that the illumination measured is received entirely without interference on the part of the observer and the instrument. Further essentials for the accurate measurement of illumination are care, skill, sound judgment and a good knowledge of photometric principles on the part of the operator.

CHAPTER VIII.

INTEGRATING PHOTOMETERS.

THE function of integrating photometers is the direct measurement of the spherical intensity and the flux emission of light sources. They are designed to accomplish experimentally the processes performed analytically and graphically by the weighted averages, the Rousseau diagram, the Kennelly diagram and other methods previously described. Two classes of integrators should be noted, (1) those which integrate the beams in a single vertical plane of light distribution and (2) those which concentrate a certain definite fraction of the total flux of an illuminant upon a diffusing screen in terms of whose intensity the total flux may be evaluated.

The Matthews integrating photometer[1] is a familiar representative of the former class. The integrator designed for use with incandescent electric lamps consists of eleven pairs of mirrors uniformly spaced by arcs of 15 deg. about a semicircular frame and so disposed as to reflect the beams of a lamp upon a vertical photometric screen at the center of the system (Fig. 42). The illumination derived from the integrated beams is balanced against that from a standard lamp and the spherical intensity is determined from the calibrated scale of the instrument. The mirrors of each pair are inclined to each other at an angle of 90 deg., each mirror making the angle of 45 deg. with the plane of the frame. A central pillar supports this frame and the mirror system. On the rear side of the pillar at the center of the mirror system is mounted a socket for the lamps to be tested. This socket may be revolved about its vertical axis by the aid of a small motor and, by releasing a stop, may be turned by steps of 15 deg. through the vertical plane of the mirror frame. Opposite this socket on the front of the pillar a photometric screen P is mounted in a vertical plane at right angles to the plane of

[1] Trans. A. I. E. E., Vol. XVIII, p. 677, and Vol. XX, p. 59. See also Bull. U. S. Bur. Stand., Vol. I, p. 255.

the frame F. Each pair of mirrors is set so as to reflect the beam emitted by the lamp X in its direction upon the screen P. Extending from the circular frame through the pillar and beyond is a horizontal slide S which supports a holder for a standard

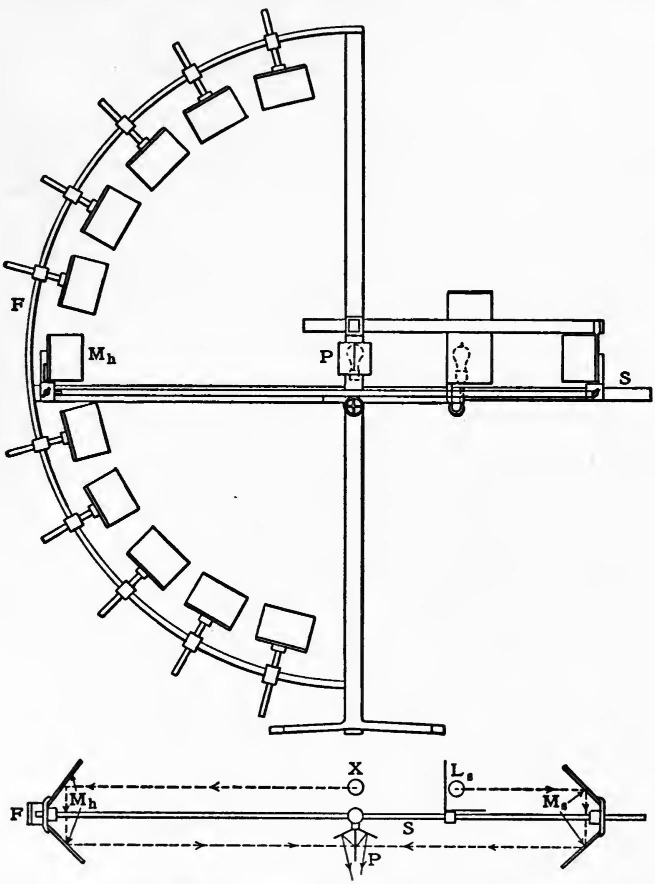


Fig. 42. — Matthews integrating photometer for incandescent lamps.

lamp of intensity I_s and a pair of mirrors M_s on a saddle movable along the slide. All the mirrors of the circular system except the pair marked M_h may be adjusted radially by their supporting rods which slide through radial bushings. The pair M_h are mounted upon a saddle which may be clamped at any desired position on S. A coupling rod is provided by which the mirrors

M_h and M_s may be connected at a proper distance and drawn along the slide in either direction by means of rack and pinion.

With all other mirrors covered and the horizontal sets thus clamped together the instrument may be utilized to measure horizontal candle-power. The standard lamp is placed in its holder and clamped to the slide in the position indicated for it. The mirrors are moved along the slide until a photometric balance is secured and the ratio of the intensities I_x and I_s is read directly from a ratio scale carried by the mirrors M_s and sliding past an index on the central pillar.

For measurements of spherical intensity it is necessary that all the mirrors of the integrating system be adjusted radially. Denoting by r_θ the joint reflection coefficient of any pair of mirrors, by I_θ the intensity of the beam emitted in their direction, by l_θ the distance traversed via the mirrors by the beam before falling upon the screen and by θ the inclination of this beam to the horizontal, the illumination of the screen derived from this beam is

$$E_\theta = \frac{I_\theta r_\theta \operatorname{Cos} \theta}{l_\theta^2},$$

assuming that the screen obeys the cosine law of diffusion. Each pair of mirrors should be adjusted to such a radial position that E_θ is proportional to $I_\theta \operatorname{Cos} \theta$ to give each beam its proper weighting in the summation on the screen. With the integrator properly adjusted and set for the measurement of mean spherical candle-power the balance is obtained by adjusting the position of the mirrors M_s on the slide. The ratio of the spherical intensity of the lamp in the rotator to the horizontal intensity of the standard lamp is read directly from the ratio scale provided.

If the standard lamp and the screen partially surrounding it are removed from the bar and the point of attachment of the ratio scale to the mirrors M_s is properly readjusted, the horizontal beam of the lamp under test may be reflected upon the screen and balanced against the integrated beams. The ratio scale of spherical intensity then indicates the spherical reduction factor of the lamp.

The holder for the lamp tested should be rotated throughout the measurements. The substitution method of measurement is to be recommended, as it obviates the need of reversing the screen and so prevents errors which would arise if the screen

should not be returned to the true vertical position. Results obtained from an instrument of this design are necessarily approximate, a 15 deg. spacing of the mirrors permitting a theoretical error of 2 per cent.[1] The accuracy may be improved by employing more mirror pairs with a smaller spacing.

The Matthews arc photometer employs as an integrator a series of mirrors uniformly spaced about the interior of a conical framework. The axis of the system coincides with that of the general photometric system and passes through the luminous center of the lamp. Direct rays from the lamp are screened from the photometer. The mirrors are so inclined to the axis as to focus upon the photometer screen *S* the beams emitted by the arc in their directions. These beams are all incident upon the screen at the same angle, making it necessary to place in the path of each beam a smoked-glass sector whose

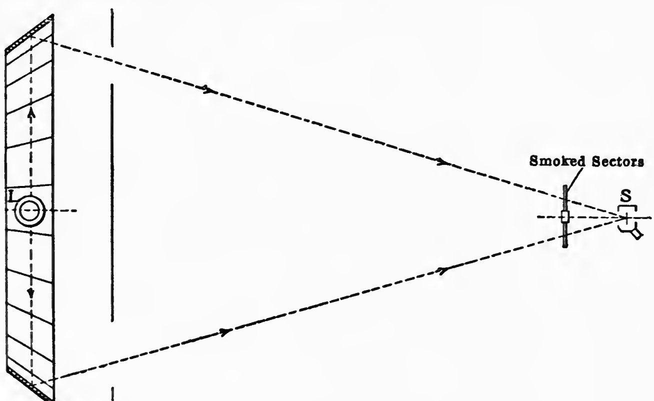


FIG. 43. — The Matthews arc photometer.

transmission coefficient is proportional to the cosine of the angle of emission of the beam, measured with the horizontal, so that each beam may have the proper weight in the summation. It is necessary to maintain the photometer screen in the focus of the mirror system, and balance must be secured by adjusting the position of the comparison lamp. The spherical intensity of an illuminant is given by this device as

$$I_{ms} = K \frac{I_s}{l_s^2},$$

[1] Bull. Bur. Stand., Vol. I, p. 255.

K being the constant of the instrument obtained by mathematical analysis or empirical calibration, I_s the horizontal intensity of the comparison lamp and l_s its distance from the screen at the time of balance. In the testing of arc lamps the double system of mirrors is of great advantage, as it minimizes the difficulty introduced by the travel of the arc. The mirror system may be employed to determine the vertical distribution of a lamp if but one pair of mirrors is uncovered at a time and their constant has been previously determined. In such measurements the smoked sectors are omitted, as weighting is not desired.

The Russell-Leonard photometer[1] also employs a circular system of inclined mirrors as an integrator, but differs from the Matthews arrangement in that the spacing of the mirrors is not equiangular, but such that each occupies a position representing one of n zones of equal area. No smoked sectors are required in its operation, as the summation of the beams on the screen yields an illumination directly proportional to the spherical intensity. If twelve zones are employed the angular spacing from the base of the system should be as follows: 23 deg. 30 min., 41 deg. 30 min., 54 deg. 20 min., 65 deg. 20 min., 75 deg. 30 min., 85 deg. 10 min., 94 deg. 50 min., 104 deg. 30 min., 114 deg. 40 min., 125 deg. 40 min., 138 deg. 30 min., and 156 deg. 30 min. If eight zones are employed the following spacing may be utilized: — 29 deg., 51 deg. 20 min., 68 deg., 82 deg. 50 min., 97 deg. 10 min., 112 deg., 128 deg. 40 min., and 151 deg. These spacings may be varied slightly to suit particular forms of light distribution, but the values suggested are probably the best general average.

The lumenmeters[2] of Prof. Andre Blondel, though little used in America, are of great practical and historical interest. By either of the two devices to be described a definite fraction of the total flux is concentrated upon a screen of small area. The total flux is evaluated in terms of the resulting luminosity of this screen, measured by simple photometric means. In the original lumenmeter the illuminant is enclosed in an opaque spherical shell with two lune-shaped apertures defined by meridian planes. This illuminant is hung at the nearer of the conjugate

[1] Bull. U. S. Bur. Stand., Vol. I, p. 255.
[2] L'Eclair. Elec., Vol. 42, p. 66.

foci of an ellipsoidal mirror. The beams emitted through the lune-shaped apertures fall upon this mirror and are focused by it upon a photometric screen placed at the more distant focus. Proper weighting is afforded by the shape of the lune-shaped apertures.

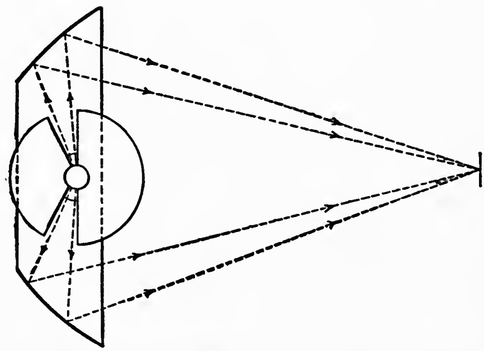


Fig. 44. — Ellipsoidal mirror lumenmeter.

A less expensive design substitutes for the ellipsoidal mirror a diffusely reflecting conical surface, bounded by two meridian circles including a dihedral angle equal to that of the apertures of the shell. This conical surface must possess very nearly perfect diffusing power, and its width must be such that the incidence angles of all the beams at the photometric screen are sensibly equal.

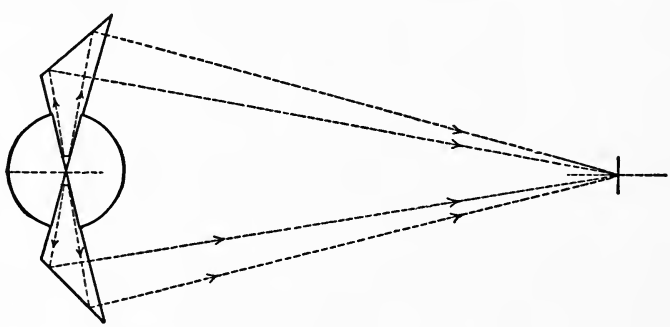


Fig. 45. — Diffusing cone lumenmeter.

The Ulbricht sphere [1] is one of the most useful accessories in the measurement of the integrated flux of luminous sources.

[1] Elek. Zeit., July 19 and 26, 1906.

It consists of a large hollow sphere coated on its inner surface with a white material of as nearly perfect diffusing power as possible. With a luminous source in the interior of the globe the illumination of its inner surface is made up of two components, the one a variable, derived from the direct rays of the lamp, and the second a uniform quantity resulting from the multiple diffuse reflection of light. The latter component is directly proportional to the total flux emitted by the lamp. A window of milk glass located in one side of the sphere is screened from the direct component of light. It is illuminated only by the uniform reflected component, and its brightness is therefore proportional to the total flux of the lamp. A photometric observation of the window may be taken from without and the spherical intensity found by multiplying the apparent intensity of the window by a previously determined constant.

For proof of the principle involved it suffices to show that the light reflected from any element dA of the interior surface falls with uniform density on all other portions of the surface. In Fig. 46 the sphere is represented by a section passing through dA, a point P whose illumination is to be considered and the center of the sphere. The boundary of this section is therefore a great circle of the sphere. Assuming that the light reflected by dA obeys the law of inverse squares and the cosine law of diffusion, denoting by I the normal intensity of dA and by dE the illumination at P derived from dA, considering first reflection only we have

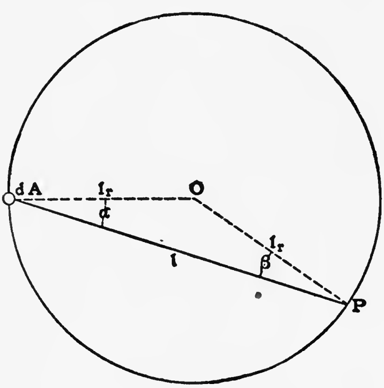


FIG. 46.

$$dE_1 = \frac{I \text{ Cos } \alpha \text{ Cos } \beta}{l^2}.$$

Since the surface is spherical every possible section is a circle, hence α and β are always equal and l equals $2\, l_r \text{ Cos } \alpha$. By substitution

$$dE_1 = \frac{I \text{ Cos}^2 \alpha}{4\, l_r^2 \text{ Cos}^2 \alpha} = \frac{I}{4\, l_r^2}.$$

dE_1 is thus seen to be independent of the relative positions of dA and P and is therefore uniform at all points on the spherical surface. The same reasoning applies equally to all points on the surface, and the total illumination at any point due to light once reflected is

$$E_1 = \sum \frac{I}{4\, l_r^2} = k_1 \phi,$$

ϕ being the total flux of the lamp. Applying similar reasoning to the illumination due to second reflection and reflection of all higher orders, by summation

$$E = E_1 + E_2 + E_3 + \ldots + E_n = (k_1 + k_2 + k_3 + \ldots + k_n)\phi = K\phi.$$

The illumination of the window is thus seen to be dependent only upon the total flux of light emitted by the illuminant within and upon the constant of the instrument.

In practice the constant of the sphere is the factor by which the apparent intensity of the window is multiplied to obtain the spherical intensity of the enclosed illuminant. It may best be determined by the aid of a large incandescent lamp whose spherical candle-power has been previously determined by some other method.

The construction of the sphere should be such as to give it great stiffness and stability and at the same time afford the greatest convenience of manipulation. A sphere intended for use with arc lamps and other illuminants of large size should be not less than five feet in diameter, though smaller spheres may be successfully operated with incandescent lamps. In the construction and manipulation of large spheres it is found convenient to construct them in two hemispherical sections divided by a meridian plane. One or both should be mounted on wheels so that the two may be readily separated and brought together. A circular opening is provided at the top of the sphere through which the illuminants may be suspended. A set of divided circular diaphragms of various sized apertures should be provided to close this space with the lamp in place. Their inner surfaces should be coated with the same material as the remainder of the sphere.

In the best practice[1] the observations are taken with both the calibrating lamp and the lamp to be tested within the sphere.

[1] Elek. Zeit., Vol. 28, p. 777.

It is recommended that both be suspended in the vertical axis of the sphere in symmetrical positions above and below its center. A screen is suspended between each of these lamps and the window. These screens should be no larger than necessary to occlude the direct rays from the window. The calibrating lamp is first lighted and the intensity of the window observed, then it is extinguished and the lamp to be tested is lighted. A photometric observation of the window is made and the spherical intensity of the lamp tested is found by multiplying the spherical intensity of the calibrating lamp by the ratio of the apparent intensities of the window. This is essentially a substitution method and this manipulation is chosen to minimize the errors introduced by the absorption of light in the screens and the opaque portions of the lamp bodies and their supports. These errors may be further reduced by covering the screens and the non-luminous portions of the lamps with some white material or by using screens of a carefully proportioned degree of translucency. Fig. 47 shows a section of an integrating sphere arranged for this method of manipulation. The coating of the inner surface must be carefully applied. It may consist of plaster paris or white paint of dull surface. Barium sulphate applied as a thick paste with a binding material of zapon lacquer is to be preferred for its adhesive qualities and its excellent diffusing surface.

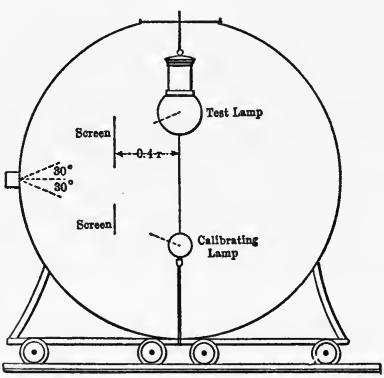


FIG. 47. — Internal arrangement of Ulbricht integrating sphere.

The Ulbricht sphere is admirably adapted to the spherical photometry of asymmetrical light sources and those of large area to which the inverse-square law applies but roughly, such as enclosed arcs, flame arcs, gas arcs and clusters. Measurements of mean hemispherical intensity may be made by mounting the lamp so that its luminous center coincides with the upper point of the spherical surface.

Dr. Carl Hering[1] has suggested an integrator which bears an

[1] Trans. Ill. Eng. Soc., Vol. IV, p. 354.

elementary resemblance to the ellipsoidal mirror of Blondel. He proposes to subdivide the hypothetical sphere about an illuminant into horizontal zones whose areas shall bear simple numerical ratios, such as 1, 2, 3, and 4. Such a division is indicated in Fig. 48. The reflecting system is designed to integrate the light in

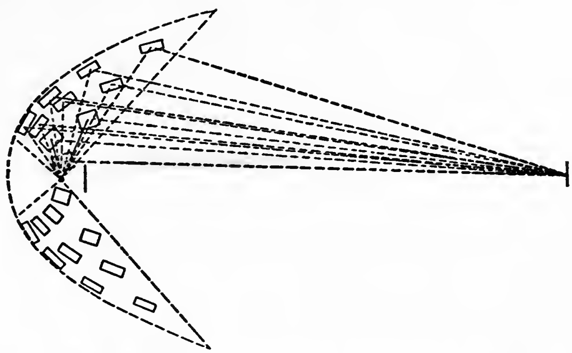


FIG. 48. — Arrangement of Hering integrator.

one or more quadrants about the light source. Each zone has as many mirrors as its proportional number, mounted tangentially to a hypothetical ellipsoidal surface with the illuminant at its nearer focus and a photometric screen at the further focus. The arrangement for two quadrants is indicated in Fig. 48. By turning the lamp about its vertical axis the mean intensity of eighty equally weighted points on the sphere of distribution may be determined from four observations. The constant of the apparatus may be readily calculated from the reflection coefficients of the mirrors.

CHAPTER IX.

INCANDESCENT ELECTRIC LAMPS.

Historical.—Early investigators attempted to utilize the heating power of the electric current to bring to incandescence thin wires of platinum, but the high cost of the material, the danger of accidental melting and the low efficiency secured precluded commercial success. Edison attacked the problem with characteristic vigor and persistence. As the culmination of a long series of discouraging experiments he discovered in 1879 that filaments of carbonized bamboo mounted in an evacuated chamber gave the desired service. For twenty years the carbon filament held the field unrivaled. A worthy competitor was then produced in the Nernst lamp, employing a luminous element of rare earth oxides. In 1905 the so-called Gem lamp with its filament of specially treated carbon came upon the market and was closely followed by a German product of still higher efficiency, the tantalum lamp. The year 1908 was made notable by the establishment of the tungsten lamp upon a firm commercial basis and by the appearance of a Nernst lamp of improved design and efficiency. The possibilities are still far from exhausted, further progress being dependent upon the conquest of a higher realm of temperature or upon the development of a refractory material of more efficient selective emission.

Rating and efficiency.—It has been the universal custom of manufacturers to rate the luminous value of all incandescent lamps except the Nernst in terms of their mean horizontal candle-power and their specific consumption in watts per mean horizontal candle-power. While much may be said from the point of view of expediency in justification of such a rating it is apparent that it is practically valueless in expressing the true illuminating power and efficiency of an illuminant unless a definite form of light distribution and a definite reduction factor connecting this rating with the mean spherical intensity be understood. A

rating based upon the mean lower hemispherical intensity would be of value only when applied to complete units, including the lamp and its accessories. The rating of illuminants in terms of the total lumens emitted or in terms of the mean spherical candle-power and of specific output in lumens per watt or mean spherical candles per watt may be commended as logical, accurate and fair.

Types of light sources.—Incandescent electric lamps divide naturally into two classes. In the first of these classes the luminous element is an attenuated filament, mounted in an evacuated glass chamber and conducting current without electrolytic action. The second class is represented by the Nernst lamp, whose glower is a pyro-electrolyte, conducting only when hot, and unsuited to vacuum operation by its electrolytic action.

Characteristics of lamp filaments.—The essential qualities of a lamp filament are (1) refractoriness, to permit its continuous operation at a high temperature; (2) high atomic weight in order that its rate of evaporation from the solid state may be as low as possible; (3) high electrical resistance, in order that the filament may be of reasonable length and cross-section to afford mechanical strength; (4) stable electrical resistance so that temperature changes may not cause fluctuations of the current; and (5) sufficient strength when mounted to withstand ordinary handling. Additional points of advantage are cheapness, possible uniformity of manufacture and selective emission favorable to the luminous spectrum.

Carbon filaments are produced by carbonizing cellulose which has first been reduced to a viscous solution and then squirted through a die into a fine thread. The carbonized thread is treated by a flashing process, which consists of raising it to incandescence in an atmosphere of hydrocarbon vapor, such as gasoline, from which carbon is liberated and deposited as a hard, lustrous coating of graphitic nature. This treatment improves the durability of the filament, raises the operating efficiency and renders its cross-section and conductivity uniform. Carbon filaments are of relatively high specific resistance, rendering their length and diameter consistent with great strength. Carbon possesses a negative temperature coefficient, *i.e.*, an increase of temperature is accompanied by a decrease of resistance. As

operated in practice their temperatures range from 1750 to 1900 deg. cent. according to the best evidence.[1]

Gem filaments are prepared by a process similar to that of ordinary carbon filaments, with additional baking at very high temperature before and after the flashing process. This treatment removes inpurities and produces structural changes in the carbon, giving it electrical properties similar to those of the refractory metals.

Tantalum filaments are drawn from metallic tantalum, a material of great strength, ductility, and electrical conductivity. Its melting point is estimated to be above 2500 deg. cent. and its atomic weight is 183. Tantalum requires very complex metallurgical treatment. Because of the low specific resistance of the element tantalum filaments are of great length and small diameter, the filament of a 40-watt, 110-volt lamp being about 25 inches long and less than 0.002 inch in diameter.

The tungsten filament has thermal and electrical properties similar to tantalum. The metallurgy of tungsten is very complex and the metal when refined is non-ductile, requiring that the filament be built up from the powdered state rather than drawn as a continuous wire. This may be accomplished by several processes. The prevailing one involves the mixing of finely divided tungsten with an organic binder into a thoroughly homogeneous mass, which is squirted as a fine thread through a die formed in a diamond. The binding material is subsequently removed by heating and the residue of tungsten welded into a continuous wire of very small diameter. Tungsten melts at a temperature estimated to be above 3000 deg. cent. and is the most refractory of the known metals. Its atomic weight is 184. Tungsten is very brittle when cold, and softens at the temperature of operation, necessitating very careful mounting.

The helion filament is at present undergoing preliminary development. It comprises an inner core of carbon upon which a coating of silicon is deposited by a process of flashing. Preliminary tests indicate that it possesses the following valuable properties: high specific resistance, strength, positive temperature coefficient at its operating temperature, refractoriness and chemical stability of an unusual order, and a marked degree of selective radiation. It is expected to combine the strength of

[1] Bull. U. S. Bur. of Stand., Vol. III, p. 341.

the carbon lamp with the efficiency and color value of the tungsten lamp at a low cost of production.

Other metallic filaments have found some vogue abroad, but have not been introduced in the American market. Among the metals employed are osmium, zirconium, iridium, alloys of zirconium-tungsten, and a zirconium-carbon combination.

The thermal properties of lamps.—The efficiency with which an incandescent body produces light is determined by three factors, viz., (1) the temperature of the radiant; (2) the total efficiency of radiation, or the ratio of the energy radiated to the energy supplied; and (3) the degree of selectivity of its radiation. The temperature of equilibrium is determined by the rate of energy supply, the emissive power of the radiant and the rate of heat conduction and convection. The second factor is dependent upon the degree of elimination of heat conduction and convection and is greatly augmented by vacuum operation. The third is dependent upon the material and surface condition of the radiant. Osmium, tungsten and tantalum appear to possess selectivity in a valuable degree.

All filaments when new exhibit a lustrous polished surface. Continued subjection to the high operating temperature causes a gradual evaporation from the surface of the filament, which becomes pitted and blackened so that its emissive power is increased and permits the radiation of the energy received at a slightly lower temperature. The inner surface of the bulb receives a deposit of the material carried from the filament which absorbs a considerable amount of light in the latter stages of a lamp's life. These factors tend to a gradual reduction of efficiency, candle-power and mechanical strength. All of these aging processes are greatly accelerated by an increase in the temperature of the filament. It is evident that the operating temperature of a lamp must be determined by a compromise between efficiency and length of life such that the ratio of the total light produced to the initial cost of the lamp plus the cost of its total energy consumption may have the maximum value. The attainment of this temperature requires the mutual adjustment of the resistance of the filament and its operating voltage with great care.

Vacuum operation of incandescent filaments is of the highest importance. Contact with gas results in a serious loss of efficiency

through conduction and convection. Because of their high temperatures filaments must be fully protected from oxidation. These results are not attained without disadvantage, as the vacuum increases the rate of vaporization of the filament. Attempts to overcome this vaporization and at the same time protect the filament from oxidation have been made by filling the lamp chamber with such gases as nitrogen, helium and argon, but it has not been found possible to increase the temperature sufficiently to outweigh the added losses by convection. Metal filament lamps require a particularly high degree of exhaustion.

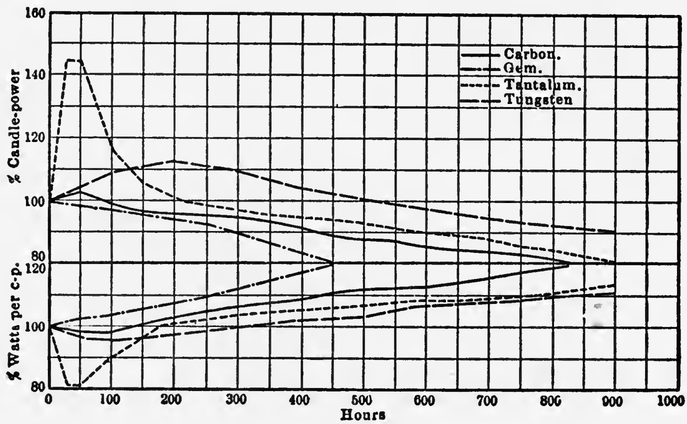


FIG. 49. — Typical life curves of incandescent lamps.

The typical life curves of Fig. 49 indicate that the first 100 to 150 hours of a lamp's performance constitute a period of instability, and that after this period the candle-power and the efficiency very gradually decline until the filament is ultimately ruptured. The *useful life* of a lamp is said to terminate at its *smashing point,* or the time at which its efficiency has so deteriorated that it may most economically be replaced by a new lamp. The useful life of carbon lamps is usually interpreted as the period of operation elapsing before the candle-power of the lamp has fallen to 80 per cent of its rated value. This definition cannot be applied to metal-filament lamps, as experience indicates that their intensities do not diminish 20 per cent within the actual life of the filament. The true value of the smashing point of any type of lamp can be found only by careful computation to determine from the average life performance the period of opera-

tion in which the total light produced has the highest ratio to the initial cost and the cost of energy consumed.

Operating characteristics.—The first relation to be noted is that between the voltage of lamps and their candle-power. The superiority of the modern metal-filament lamps in this particular should be noted. Of equal importance is the relation of terminal voltage and the life of the filament, as indicated in Fig. 51.

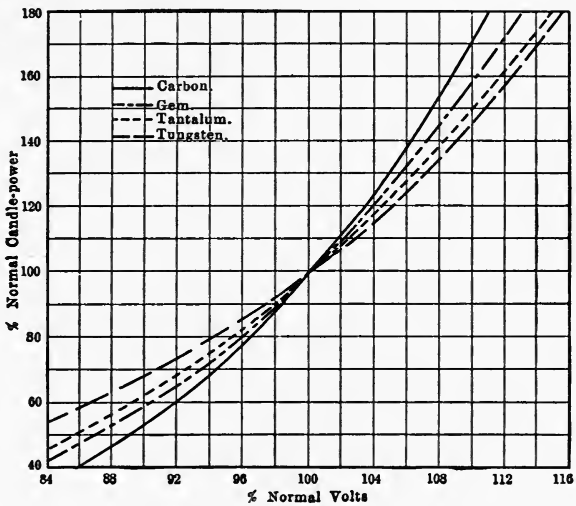


Fig. 50. — Relation of candle-power to terminal volts.

The relation of power consumption to terminal voltage is shown in Fig. 52, and the relation of specific consumption to terminal volts in Fig. 53.

The above curves make clear the necessity for the close regulation of voltage on constant-potential lighting circuits. Slight reductions in voltage cause the light to fall far below the normal, while excess voltage greatly diminishes the life of the lamps, though temporarily raising the efficiency. Satisfactory performance is not to be expected from lamps subjected to varying voltage. The rate of deterioration at excess voltages is so great that the return to normal conditions in the circuit may find the lamp too dim for longer service. Unless the cost of energy is very high and the cost of renewals very low the practice of over-running lamps is unwarranted. For the protection of cus-

tomers, the permissible limits of voltage regulation are in some cases fixed by law.

Where lamps are operated by alternating currents the effects of frequency are of considerable importance. Lamps operated at very low frequencies display maxima and minima of intensity

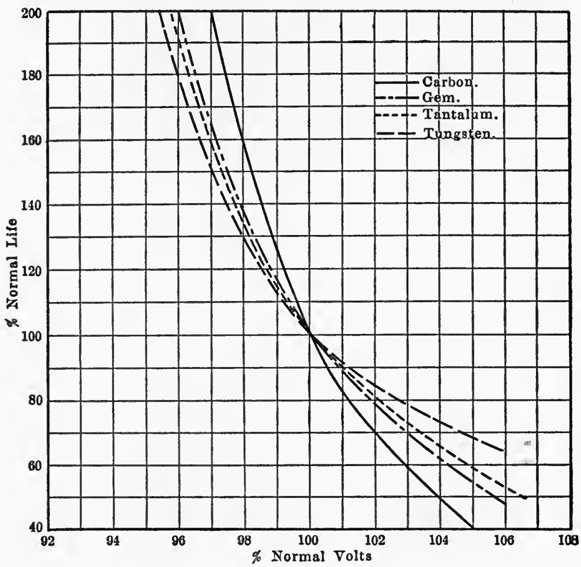


FIG. 51. — Relation of life of lamps to terminal volts.

coincident with the cyclic variations in the current. At higher frequencies the heat storage of the filament and the optical persistence of the retina tend to render this flicker imperceptible. A marked positive temperature coefficient of resistance tends to smooth out variations of current and assists in the reduction of flicker. Relatively large heat-storage capacity in the filament tends to reduce the cyclic variations in temperature. The vanishing frequency of flicker is also dependent upon the color and the size of the surface viewed. The relative sensitiveness of various incandescent lamps to the frequency is indicated by the following curves. (Fig. 54.)

The conclusion may be drawn that for frequencies below 30 cycles only low-efficiency carbon lamps are satisfactory, while the metal-filament lamps are satisfactory at frequencies exceeding

40 cycles. For commercial lighting the prevailing frequency of 60 cycles is entirely satisfactory.

The effect of frequency upon the life of a filament is worthy of note only in the case of the tantalum lamp. The aging of these filaments is accompanied by an apparent crystallization of the

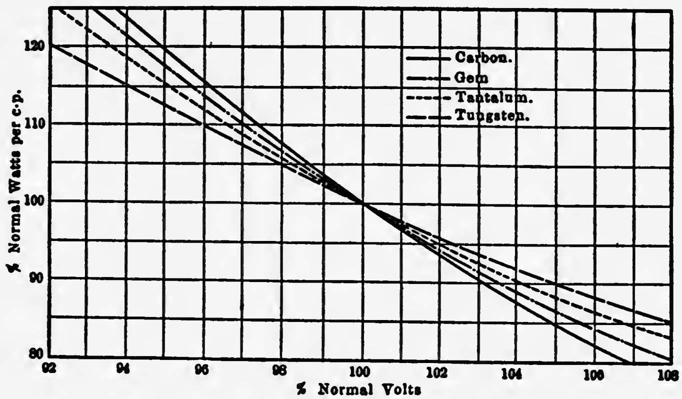


FIG. 52. — Relation of energy consumption to terminal volts.

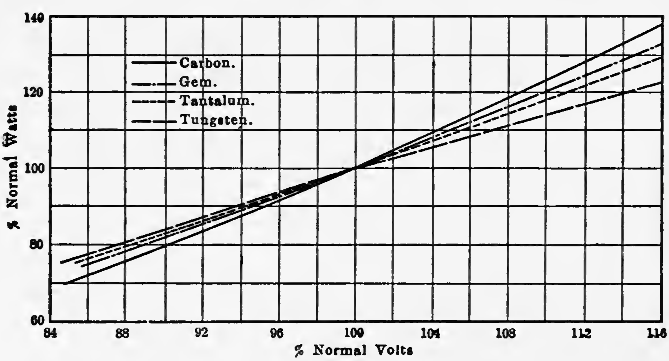


FIG. 53. — Relation of specific consumption to terminal volts.

metal which greatly reduces its tensile strength. The process proceeds slowly with direct current, but is greatly accelerated by alternating current especially at the higher frequencies. This effect may be due to vibrations set up by the inductive action of the many parallel elements of the filament, but is more probably due to the cyclic variations in temperature. In consequence, the life of filaments operated by 60-cycle alternating current is about 40 per cent lower than that obtained with direct current.

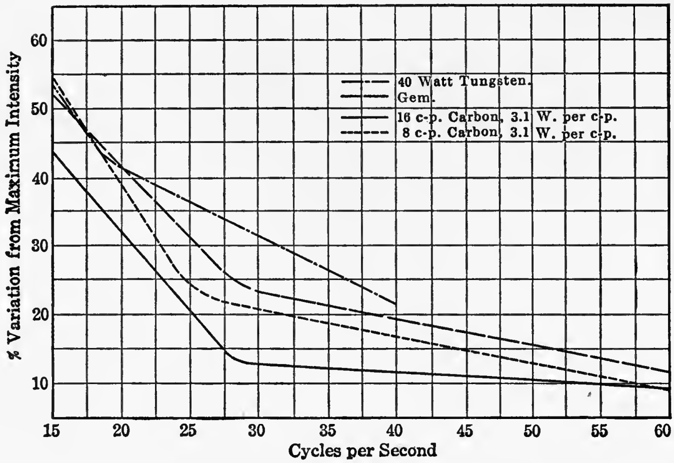


Fig. 54. — Sensitiveness of lamps to frequency.

Incandescent lamp data are given for all the commoner sizes and varieties in Table VII. The values given are general averages, and individual lamps may show considerable variation from the average in any of the several items.

Frosted bulbs.—The frosting of bulbs is resorted to as a means of decreasing the intrinsic brilliancy of lamps and so improving the softness and diffusion of their light. It has long been noted that the useful life of carbon filaments enclosed in frosted bulbs is reduced from 40 to 50 per cent. This loss has often been attributed to a supposed confinement of heat by the frosted surface and a resulting increase in the rate of filament decay. Investigation [1] shows that the rapid rate of reduction in candle-power is due in part to the multiple reflection of light through the glass and the deposit which accumulates upon its interior and in part to the tendency of the frosted surface to gather dust and dirt. When lamps are almost entirely covered by shades or reflectors it is sufficient to frost only the lower portion of the bulb, with a reduction in life and intensity so small as to be of little consequence. Complete frosting causes an absorption of from 12 to 15 per cent of the light.

Forms, mounting and light distribution of filaments.—The forms of filament and the methods of mounting most commonly

[1] Bull. U. S. Bur. Stand. Vol., III, p. 341.

TABLE VII. — AVERAGE PERFORMANCE OF AMERICAN INCANDESCENT LAMPS.

Type of lamp.	Rated hor. c.-p.	M. s.c.-p.	Rated watts per c.-p.	Watts per m.s.c.-p.	Total watts.	Hours useful at rated voltage.
Carbon (95 to 130 volts.)	8	6.6	3.1	3.76	24.8	300
	18	6.6	3.5	4.33	28.6	790
	10	8.3	3.1	3.74	31.0	350
	10	8.3	3.5	4.31	35.7	900
	16	13.2	3.1	3.76	49.6	450
	16	13.2	3.5	4.24	56.0	830
	20	16.5	3.0	3.69	60.8	370
	20	16.5	3.5	4.22	69.6	770
	24	19.8	3.1	3.76	74.4	400
	24	19.8	3.5	4.52	89.5	1060
	32	26.4	3.1	3.76	99.2	430
	32	26.4	3.5	4.33	114.2	900
Gem (At upper voltage.)	16	13.0	2.5	3.08	40.0	450
	20	16.5	2.5	3.03	50.0	450
	32	26.1	2.5	3.06	80.0	450
	40	32.6	2.5	3.06	100.0	450
	50	41.0	2.5	3.06	125.0	450
	75	61.5	2.5	3.06	187.5	450
	100	82.0	2.5	3.06	250.0	450
Gem (At middle voltage.)	14.6	11.9	2.65	3.26	38.8	640
	18.3	15.1	2.65	3.21	48.5	640
	29.3	23.9	2.65	3.18	77.6	640
	36.7	30.0	2.65	3.23	97.0	640
	45.9	37.6	2.65	3.23	121.3	640
	68.7	56.3	2.65	3.23	182.0	640
	91.7	75.2	2.65	3.23	242.5	640
Gem (At lower voltage.)	13.3	10.7	2.83	3.53	37.8	940
	16.7	13.84	2.83	3.42	47.3	940
	26.7	21.8	2.83	3.47	75.6	940
	33.5	27.5	2.83	3.42	94.0	960
	41.8	34.3	2.83	3.42	117.4	940
	62.7	51.4	2.83	3.42	176.0	940
	83.0	68.0	2.83	3.45	234.8	940
Tantalum (100 to 125 volts.)	12.5	8.9	2.50	2.53	25.0	900 [1]
	20	15.8	2.00	2.53	40.0	900 [1]
	40	31.6	2.00	2.53	80.0	800 [2]
Tungsten (100 to 125 volts.)	20	15.6	1.25	1.60	25.0	800
	32	24.0	1.25	1.62	35– 45	800
	48	37.6	1.25	1.59	50– 70	800
	80	62.9	1.25	1.58	85–115	800
	200	152.0	1.25	1.64	230–270	800

[1] These values for direct current only; 500 hr. for 60-cycle alternating current.
[2] This value for direct current only: 500 to 700 hr. for 60-cycle alternating current.

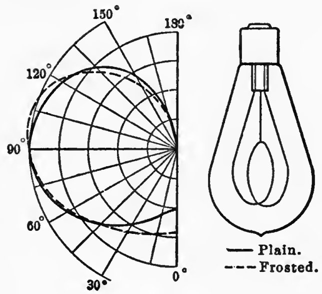


Fig. 55.

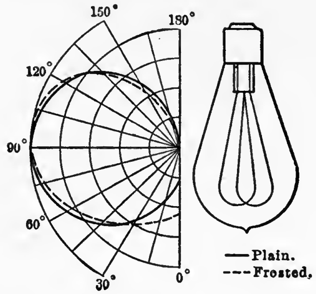


Fig. 56.

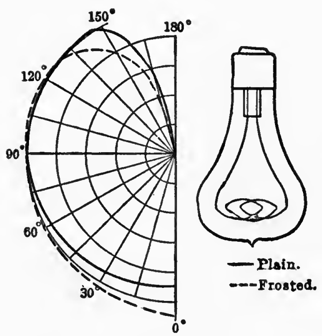


Fig. 57.

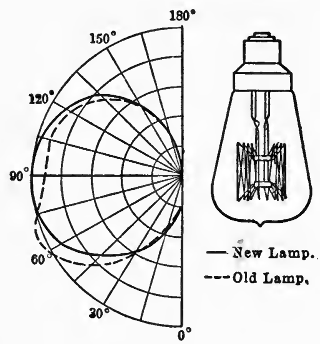


Fig. 58.

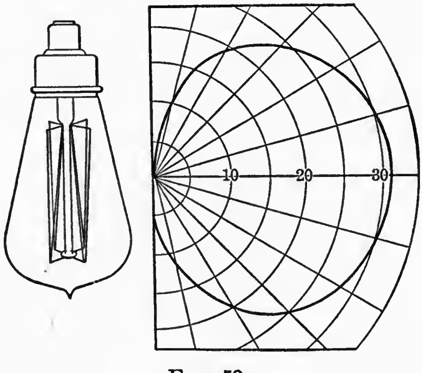


Fig. 59.

employed with carbon, gem, tantalum and tungsten lamps are indicated in Figs. 55 to 59, together with the mean vertical distribution curves for each type. In several of the diagrams the effect of frosting the bulb on the light distribution is also shown.

Acceptance and rating tests.—As in all other branches of technical industry the results obtained in incandescent lighting are dependent upon the quality and accurate rating of the appliances involved. When lamps are bought in large quantities accurate specifications and careful inspection are essential to determine and regulate the grade of the lamps secured. While common practice holds the uniformity of lamps within general limits, no universal set of specifications prevails. Those adopted by the United States government to regulate its purchases embody many features which may well serve as models to other extensive purchasers. These specifications[1] provide for the careful inspection of the quality of the bulbs, the mechanical and electrical security of the bases, the symmetry and permanence of the filaments, the construction of the leading-in wires, the quality of the vacuum, the accuracy of the candle-power and efficiency rating and the life performance of the lamps. These specifications are published by the Bureau of Standards.

The target diagram is a useful accessory in checking up the accuracy of the rating of a lot of lamps by photometric test. Fig. 60 represents such a diagram applied to a lot of 16-candle-power lamps rated at 3.5 watts per candle-power. In this diagram the candle-powers are laid off on the axis of ordinates and the watts consumption on the axis of abscissæ. Horizontal lines are laid off to indicate the permissible variation of individual lamps from the rated candle-power, vertical lines to indicate the permissible limits of variation of power consumption, enclosing the figure *abcd*. A slanting line *ef* is drawn through points corresponding to an energy consumption of 3.5 watts per candle-power. A rectangular figure *a'b'c'd'* is laid off to indicate the permissible variation in the performance of the mean of the lot from the rated value. The performance of each lamp is indicated upon this diagram by a black dot and the mean performance by a dot surrounded by a circle. The degree to which the

[1] Special Pamphlet by U. S. Bur. Stand.

lamps tested conform to the specified limits of variation is directly indicated by such a diagram.

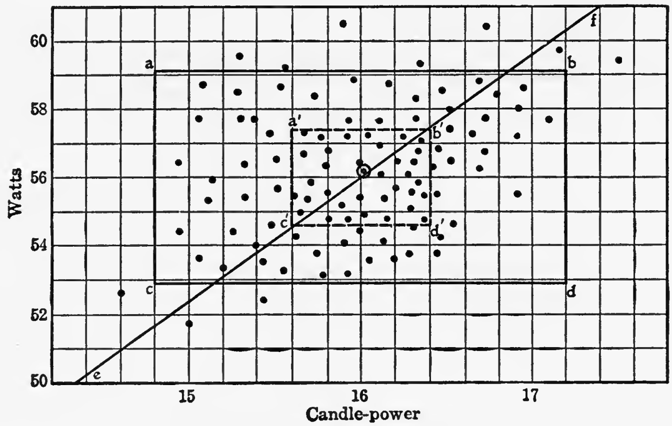


Fig. 60. — Target diagram.

Life tests are made to determine the life performance of lamps by subjecting them to their rated voltage and at stated intervals measuring their candle-power and power consumption. During such tests the voltage applied to the lamps should not vary from the rated value by more than 0.25 per cent if accuracy is desired. Life tests conducted in this manner are expensive, require a long period and demand close attention. When comparative results only are sufficient the lamps may be run at a considerable over-voltage and the hours of actual burning reduced to the hours of normal operation corresponding by the aid of the relations shown in Fig. 51, this being known as a compromise method.

Constant-current lamps for street lighting are increasing in use rapidly. They are generally manufactured with thick filaments of low resistance so that many of them may be operated in series on a single circuit operated by constant-current machinery. This arrangement permits great economy in power distribution and lamp operation. The lamps are designed to operate at the current values standard for series arc circuits, permitting the use of the same generating and transforming apparatus. Table VIII indicates the ratings, specific consumption and general performance data of series incandescent lamps.

TABLE VIII. — RATING AND PERFORMANCE OF SERIES INCANDESCENT STREET LAMPS.

Type of lamp.	Rated c.-p.	Amperes.	Volts.	Watts per c.-p.	Total watts.	Hours life.
Carbon	25	3.0	29.20	3.5	87.5	1000
	25	3.5	25.00	3.5	87.5	1000
	25	5.5	15.91	3.5	87.5	1000
	25	6.6	13.26	3.5	87.5	1000
	40	3.0	46.70	3.5	140.0	1000
	40	3.5	40.00	3.5	140.0	1000
	40	5.5	25.45	3.5	140.0	1000
	40	6.6	21.21	3.5	140.0	1000
	40	7.5	18.66	3.5	140.0	1000
	60	3.5	60.00	3.5	210.0	1000
	60	5.5	38.18	3.5	210.0	1000
	60	6.6	31.82	3.5	210.0	1000
	60	7.5	28.00	3.5	210.0	1000
Gem	25	3.0	22.50	2.7	67.5	800
	25	3.5	19.27	2.7	67.5	800
	25	5.5	12.26	2.7	67.5	800
	25	6.0	11.25	2.7	67.5	800
	40	3.0	36.00	2.7	108.0	800
	40	3.5	30.86	2.7	108.0	800
	40	5.5	19.64	2.7	108.0	800
	40	6.6	16.36	2.7	108.0	800
	40	7.5	14.40	2.7	108.0	800
	60	3.5	46.29	2.7	162.0	800
	60	5.5	29.45	2.7	162.0	800
	60	6.6	24.55	2.7	162.0	800
	60	7.5	11.60	2.7	162.0	800
Tungsten	40	4.0	13.50	1.35	54.0	1000
	40	5.5	9.82	1.35	54.0	1000
	40	6.6	8.19	1.35	54.0	1000
	40	7.5	7.20	1.35	54.0	1000
	60	4.0	20.25	1.35	81.0	1000
	60	5.5	14.71	1.35	81.0	1000
	60	6.6	12.27	1.35	81.0	1000
	60	7.5	10.80	1.35	81.0	1000

NOTE. — Carbon lamps are also made for operation at 4 watts per candle-power where very poor regulation obtains. Carbon and gem lamps are used to some extent on circuits at 1.75 amperes and 3 amperes. Estimates of life given apply only to circuits of good voltage and current regulation. Tungsten lamps may vary as much as 8 per cent from the rated candle-power, the specific consumption rating of 1.35 watts being closely adhered to.

Vacuum tests.—A rough test may be made of the vacuum of a lamp by noting the freedom of vibration of the filament when the lamp is agitated, marked damping indicating a deficient vacuum. A more refined test may be made by discharging an induction coil through the lamp chamber in parallel with a half-inch spark gap. The presence of gas in excess will then be indicated by a well-marked bluish or purplish glow.

The Nernst lamp is conspicuous for its many radical departures from the traditions of incandescent lamp manufacture. The luminous element or glower comprises a thin hollow cylinder of rare earth oxides. Zirconia and yttria form the basis of the mixture, but other oxides are present in small quantities and are of considerable value. The glowers owe their conductivity in part to electrolytic action and are but slightly conducting when cold. They are sufficiently stable to permit continued operation in air at a temperature exceeding 2000 deg. cent. for periods exceeding 600 hours. Vacuum operation of glowers is impracticable, as the vacuum is destroyed by the products of electrolytic action. Artificial heating is required to bring the glowers to the temperature of conductivity. The large negative temperature coefficient of the glowers renders the current unstable at the operating temperature and necessitates a series ballast of large positive temperature coefficient to compensate changes in the glower resistance accompanying a change in the potential applied.

The glowers of the early types of lamps were adapted only to alternating-current operation, but more recently satisfactory direct-current glowers have been produced, showing an efficiency and life but little below the alternating-current glowers. In multiple-glower lamps provision is made for their individual renewal. The leading-in wires terminate in small metallic beads which are held in the clips of a spring holder, insuring uniform horizontal tension and maintaining the glowers at the proper distance from the heaters and the reflecting canopy.

The heater element consists of platinum wire wound helically upon a thin porcelain rod and imbedded in a refractory cement. The heater for single-glower lamps is a single cylinder parallel to and above the glower, both being mounted below a porcelain holder with a screw base for attachment to the lamp body.

The heater of the multiple-glower lamp is bent back and forth into several parallel elements and is mounted upon a porcelain wafer independently of the glowers. This wafer engages with a pair of horizontal bayonet contacts above the glowers.

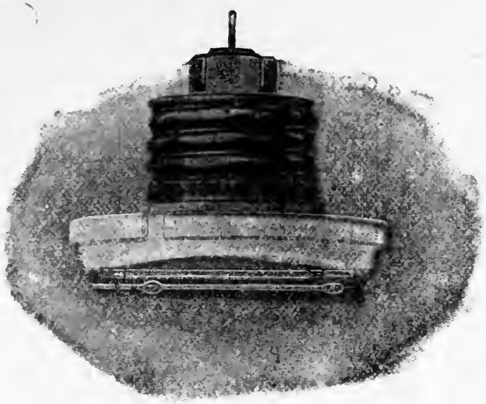


FIG. 61. — Renewable element of single-glower lamp.

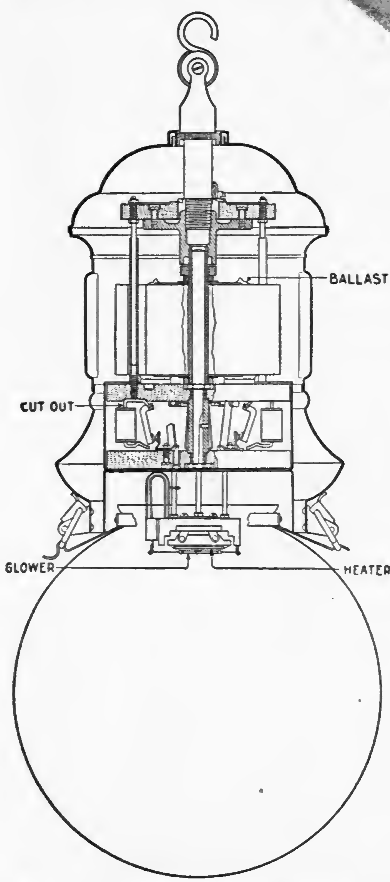


FIG. 62. — Internal arrangement of multiple-glower lamp.

In lamps of the latest type the heater element is so designed that it glows with incandescence immediately upon closing the circuit and furnishes light until the glowers themselves become active, thus rendering the lamp practically instantaneous in its starting.

The ballasts consist of thin iron wire in small glass bulbs filled with hydrogen, which protects the iron from corrosion and assists in the dissipation of its heat. Thin sheets of metal attached to the metallic case of the lamp press against the ballast bulbs and increase their radiating power. The ballasts therefore require infrequent renewal.

The cut-out switch operates electromagnetically by the current in the glower circuit and breaks the heater circuit when the operating conditions have been attained.

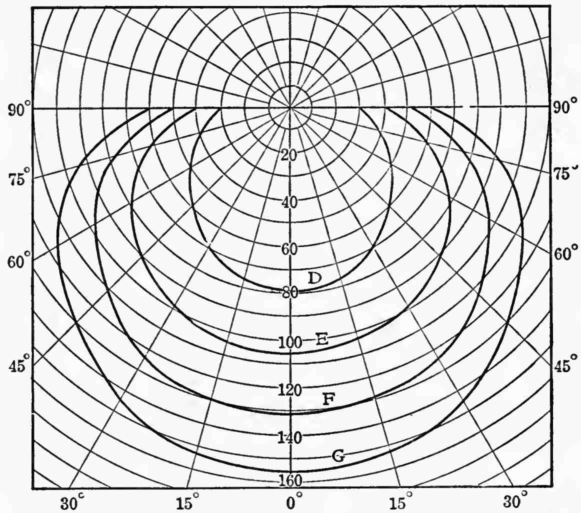


Fig. 63. — Light distribution of single-glower lamps.

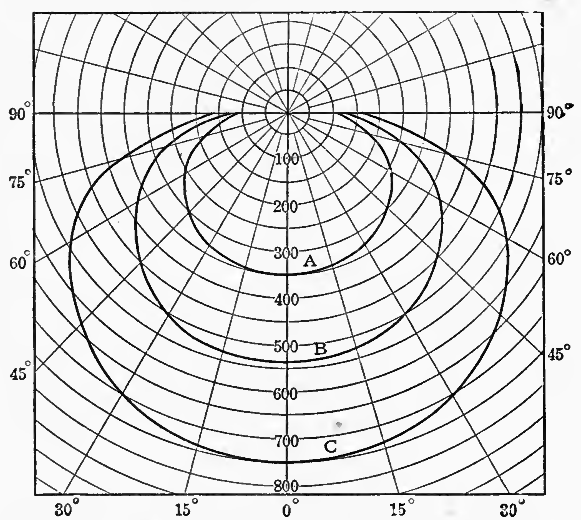


Fig. 64. — Light distribution of multiple-glower lamps.

Light distribution.—The horizontal arrangement of the luminous elements below white porcelain reflecting surfaces gives the

Nernst lamp an inherent downward distribution of light superior to any other electric illuminant. The curves of Fig. 63 give the lower hemispherical distribution of single-glower lamps and those of Fig. 64 the distribution of multiple-glower lamps, clear glass globes being used in each case.

The rating and efficiency of Nernst lamps are summarized in Table IX, which refers to a test of lamps equipped with clear globes.

TABLE IX. — OPERATION AND LIFE OF NERNST LAMPS.

Lamp Rating.	Voltage.	Current.	Glassware, inches.	Maximum c.-p.	M. h. c.-p.	Mean hemi. efficiency.	Actual wattage under test.
Glower:							
1 (66 watt)	110	0.6	4	74	50	1.38	69(110 v.)
1 (88 ")	220	0.4	4	105	77	1.2	92
1 (110 ")	110 and 220	1.0 and 0.5	5	131	96.4	1.2	115
1 (132 ")	110 and 220	1.2 and 0.6	6	156	114	1.2	136.8
2 (264 ")	220	1.2[1]	8	345	231	1.2	276
3 (396 ")	220	1.8	8	528	359	1.15	414
4 (528 ")	220	2.4	8	745	504	1.09	552

[1] All multiple-glower, 220-volt type, a.-c. lamps can be operated on 110-volt service by use of a small converter coil.

NOTE. — All lamps for either a.-c. or d.-c. service.

Part.	Hours Life.							
	Direct current.		Alternating current.					
			25 Cycle.		60 Cycle.		133 Cycle.	
	110 v.	220 v.	110 v.	220 v.	110 v.	220 v.	110 v.	220 v.
Glower	......	600	......	400	......	800	......	800
Heater	......	3000	3000	3000	3000	3000	3000	3000
Ballast	15000	15000	15000	15000	15000	15000	15000	15000
Screw burner	600	600	400	400	800	800	800	800

Operating characteristics.—Nernst glowers operating in air are subject to heat losses which impair their efficiency. They are always semi-enclosed by glass balls which stagnate the air circulation and partially offset this loss. Additional losses occur in the auxiliary devices of the lamp and in the glower terminals.

Proper proportioning of the ballasts gives the lamp a unique regulation on circuits of varying potential, as may be seen from the curves of Fig. 65. It is desirable to equip the lamps with alabaster globes to give the light a safe and pleasing degree of diffusion. The resulting reduction in efficiency of from 20 to 25 per cent due to light absorption is more than repaid by the improvement in the quality of the light.

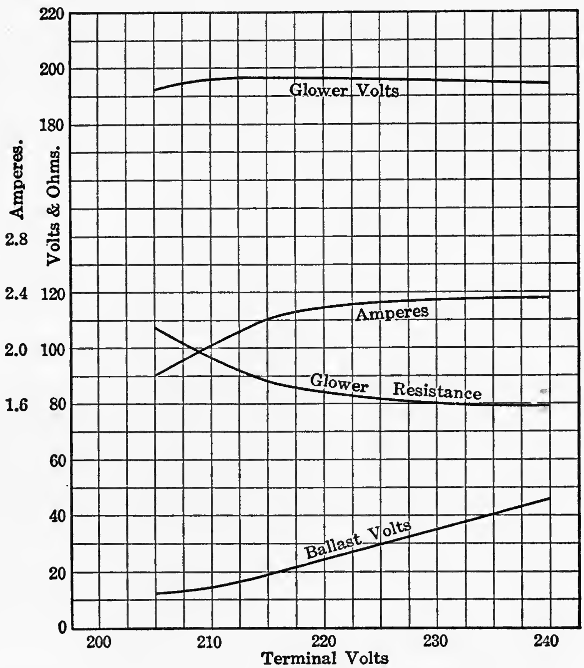


FIG. 65. — Operating characteristics of Nernst lamps.

General advantages claimed for the Nernst system are high efficiency, excellent inherent distribution, flexibility of size and general adaptation, low cost of maintenance when the lamps are given proper care, mechanical durability, excellence of color and pleasing quality of light. The lamps are of high first cost and the multiple-glower sizes are apt to require skilled attention, though the maintenance of the single-glower lamps is very simple. The Nernst lamp has been most successful where units of intermediate size between arcs and incandescent lamps of the common sizes are desirable.

CHAPTER X.

THE ELECTRIC ARC AND THE VACUUM TUBE.

THE conducting power of gases is employed to convert electrical energy into light by two distinct processes, the *electric arc,* in which the conducting vapor is derived from the electrodes by electro-vaporization, and *the vacuum tube discharge,* by which a column of rarefied gas conducts when subjected to a high alternating potential.

The electric arc was the pioneer electrical illuminant, its phenomena having been known and utilized for more than a century. The present rate of its development, however, indicates that its practical possibilities are far from being exhausted. Investigation shows that the arc conducts current through streams of ionized vapor derived from the electrodes and that the part played by the stream of negative electrons released at the cathode is of major importance. The arc may be supported solely by the vapor produced at the cathode and the anode given indefinite life if provided with sufficient cooling facilities. As conductivity continues only in the presence of plentiful and continuous ionization at the cathode, interruptions and reversals of the current generally result in the cessation of the arc, the carbon arc being the only practical exception to this rule. In no other case can the arc be maintained by an alternating current unless the potential be so high that a disruptive spark discharge passes after each reversal and reëstablishes the arc.

Electrical characteristics of the arc.—Exploration of the distribution of energy and potential in the arc shows that each has three components, one localized at the anode, a second at the cathode and the third distributed through the arc stream. The potential expended at the electrodes varies but little with the current and depends rather upon the materials composing the electrodes. The potential fall in the arc proper depends upon the material forming the arc and obeys Ohm's law but is complicated by the changes in cross-section and density of the arc accom-

panying changes of current. For the arc formed in air Steinmetz[1] suggests the following theoretical equation:

$$e = e_0 + \frac{k\,(l + l_1)}{\sqrt{i}},$$

e being the total arc potential, e_0 the constant voltage drop at the electrodes and the second term the potential consumed in the arc stream; k and l_1 are constants depending upon the material of the electrodes, l is the length of the arc in inches and i the current in amperes. For the carbon arc $e_0 = 36$, $k = 130$, and $l_1 = 0.33$. For the magnetite arc $e_0 = 30$, $k = 123$ and $l_1 = 0.05$. The equation for the mercury arc formed in a closed tube with a non-volatile anode becomes

$$e = 13 + \frac{l}{1.68\,l_d - 0.114\,i - \frac{1.3\,l_d^2}{i}},$$

where l_d is the diameter of the arc in inches. The above equations are of a practical significance, as they show the inherent instability of arc conduction; that is, the inverse relationship

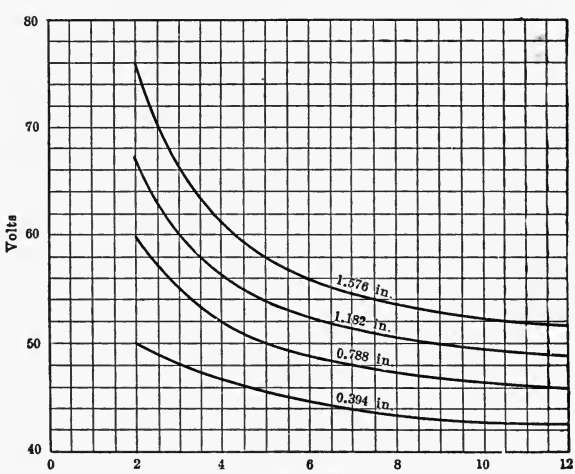


Fig. 66. Electrical instability of carbon arcs.

of current and pressure. This instability requires that the arc be given external regulation if its current and pressure are to maintain a stable equilibrium.

[1] Trans. A. I. E. E., Vol. XXV, p. 789.

In the alternating-current arc the resistance undergoes cyclic changes synchronous with the cycles of current due to the expansion and contraction of the arc. This results in a distortion of the current wave and gives the arc an inherent power-factor similar to an inductive impedance, though no true time lag exists. This power-factor varies somewhat with the form of the pressure wave and the quality of the carbons. The average value approximates 0.85.

Luminous characteristics.—The light of the arc is the result of two phenomena, the incandescence of the electrodes and the luminescence of the arc vapor. The former phenomenon predominates in the carbon arc and the latter in the luminous arcs. The spectrum of the carbon arc is that of incandescent carbon at the arc temperature, with a single strong violet band superposed by the luminescence of the carbon vapor. Luminous arcs display band spectra, the fundamental spectrum being characteristic of the cathode material. The light may be greatly modified and intensified by the superposition of the spectra of materials vaporized from the anode which luminesce in the arc. For more detailed consideration the practical arc illuminants may be grouped into three classes: —

(1) Those which produce light by the incandescence of intensely hot refractory electrodes.

(2) Those which produce light mainly from the luminescence in the arc of mineral salts vaporized from carbon electrodes.

(3) Those which produce light by the luminescence of metallic vapor derived solely from the cathode, the anode being unconsumed.

The carbon arc is the only practical representative of class one. The arc blast formed at the cathode impinges upon the anode, forming an incandescent crater of boiling carbon at a temperature of about 3600 deg. cent. In the open direct-current arc the crater is the source of 85 per cent of the light. The cathode is similarly heated, though to a less degree, and yields about 10 per cent of the light, the remaining 5 per cent being the blue band from the arc stream. The luminous efficiency of the crater alone is very high, but the gross efficiency of the arc is greatly reduced by heat convection and conduction and by the inefficient expenditure of energy in the arc stream. In the alter-

nating-current arc no pronounced crater is formed and the two carbons contribute about equally to the light.

Arc lamp carbons are produced from a mixture of finely powdered coke and pitch. They are formed by forcing this mixture through a die or by molding it under heavy pressure, the rods then being baked at a high temperature to harden them and drive off all volatile matter. Molded carbons are cheaper to produce and are very largely used in open arcs. Long carbons for this class of service are usually copper-plated to increase their conductivity. Cored carbons are forced with a cylindrical channel at the axis which is subsequently filled with a mixture of powdered carbon and a volatile salt. The use of cored carbons tends to reduce the resistance of the arc, to lower the voltage for a given length, to increase the arc length for a given voltage, to steady the arc in its position and to give it greater stability because of the plentiful vapor supply afforded.

The open arc is characterized by the rapid consumption of carbons, the heavy current and short arc length required for its stable operation, the extreme brilliancy of its light and by its high efficiency of light production. In direct-current lamps the anodes are consumed at a rate ranging from 1 to 2 inches per hour, depending upon their quality, their diameter and the strength of the current. Negatives are consumed at half this rate. In alternating-current arcs the consumption is equal in both carbons, the rate being between 1 and 1.5 inches per hour. This rapid rate of consumption is the result of unrestricted oxidation. It adds greatly to the cost of renewals and the labor of trimming and requires that the carbons be very long to give a life per trim equal to a single night's operation. In many lamps the desired life per trim is secured by the use of two sets of carbons, the second set being automatically put into service when the first is exhausted. The light of the open arc is unsteady and of a harsh nature, due to the sharpness and intensity of its shadows. Though a very efficient source of light, the open arc has been largely replaced by other types because of the above disadvantages.

The enclosed arc is characterized by the long life of its carbons, obtained by the restriction of oxidation; the greater arc length and lower current which permit its stable operation; reduced brilliancy and lower efficiency as compared with the open arc.

Carbons of the ordinary sizes burn but $\frac{1}{16}$ to $\frac{1}{8}$ inch per hour, permitting a life per trim of from 100 to 150 hours in the direct-current lamp and of from 80 to 100 hours in the alternating-current lamp. The crater is less pronounced in the enclosed arc and a greater proportion of the energy is expended in the relatively non-luminous arc stream than in the open arc. Light is absorbed in the enclosing globes to the extent of from 8 to 40 per cent, depending upon the nature of the glass. As the carbons burn away a deposit of ash accumulates on the interior of the inner globe and results in absorption of light, which varies from about 5 per cent with the highest grade of carbons to about 30 per cent with the poorer grades. The enclosed arc is therefore less efficient than the open arc of the same consumption. Its light is of a bluer color, due to the increased proportion derived from the arc stream, but it is generally better distributed and diffused for purposes of general illumination.

Regulation of carbon arcs.—There are two general systems of arc lamp operation, the series system, in which all the lamps of a given circuit are operated in series with a constant current supplied by special generating or transforming equipment, and the multiple system, in which the arcs are operated in parallel from constant potential mains. The former system provides external regulation of the current, but requires that each lamp regulate for itself the length and voltage of the arc. The multiple system furnishes inherent voltage regulation, but requires each lamp to regulate its current and the length of its arc. The starting of the arc requires that the carbons be brought into contact and separated to the proper length. Typical arc lamp mechanisms designed to fulfill these functions are illustrated in the following diagrams.

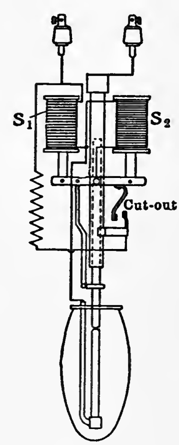


Fig. 67. Mechanism of a series carbon arc.

Series lamps are regulated by the differential action of two solenoids as indicated in Fig. 67. S_1 is a series coil and S_2 a high-resistance coil shunted across the arc. The plungers of the two solenoids are attached by a lever to a clutch holding the upper carbon, the action of the series coil tending to lift the clutch and the action of the shunt coil to release it.

Dashpots are provided to prevent the violent action of the plungers. A cut-out switch is required to furnish a continuous path when for any reason the circuit through the arc is interrupted. The cut-out is usually closed when the shunt coil alone is active. In series with the cut-out is a starting resistance. When the lamp is idle the carbons are normally together and the cut-out closed. When the current is switched on, the low-resistance path through the carbons receives a current sufficient to energize S_1 which draws out the arc and opens the cut-out. S_2 becomes energized by the potential across the arc and opposes S_1, equilibrium being attained when the arc has its proper length. As the arc lengthens by the burning apart of the carbons its potential rises and strengthens S_2, momentarily releasing the clutch and allowing the carbon to fall. The proper length is restored by the interaction of S_1 and S_2. Should the circuit through the arc be accidentally broken, S_2 alone would be energized and would immediately close the cut-out, preventing the interruption of the circuit of which the lamp is a part. Alternating-current mechanisms differ from those in direct-current lamps in that the plungers are of laminated structure and that the shunt coil is provided with a compensating reactance to allow its adjustment to the frequency of the circuit.

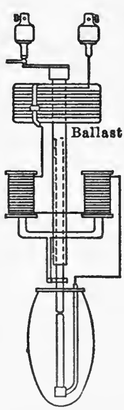


Fig. 68. Mechanism of a multiple arc lamp.

The mechanisms of multiple lamps are very simple. A ballast coil is provided, consisting of resistance in direct-current lamps and of reactance in alternating-current lamps. A solenoid in series with the ballast and the arc actuates the upper carbon by means of a clutch. The interaction of the ballast and the solenoid maintains the current at a fairly constant value and compensates for slight variations in the pressure supply. In direct-current lamps the loss of energy in the mechanism amounts to from 30 to 50 per cent. In alternating-current lamps this loss is reduced by the use of reactance, but the power-factor of the lamp is reduced to about 65 or 70 per cent.

The light distribution and efficiency of arc lamps are very largely dependent upon the conditions of operation, the form of the energy supplied, the nature of the enclosing glassware,

its cleanliness and the quality of the carbons. Enclosed arcs are less efficient than open arcs for the reasons already stated. Alternating-current arcs are about 20 per cent less efficient than direct-current arcs of the same class. Arcs operated with carbons of small diameter are more efficient than those using larger carbons, but give a proportionately lower life per trim. This increase in efficiency is due to the higher current density, the reduced heat conduction and to the reduction of the obstructing surface of the lower carbon to the downward light. The form of the distribution depends upon the arrangement of the carbons, the type of reflector if one is employed, the diffusing properties of the glassware and the height of the arc in the enclosing globe. Curves and other data relating to arc illuminants are to be considered as illustrative and typical rather than of general application. Figs. 69 and 70 together with the appended performance data may be taken as typical of the average practice with carbon arcs.

Quality of the light from arcs.—The light of the carbon arc is of great brilliancy and harshness, casting sharp and dense shadows. When opalescent globes are used the loss of light by absorption amounts to from 20 to 40 per cent, but is fully offset by the improved illuminating quality of the light, the diffusion enabling the eye to utilize the light to better advantage. Opalescent glass may have additional value in balancing the spectrum through selective absorption of violet rays. The light of the arc is necessarily rendered unsteady by the travel of the arc about the ends of the carbons, but this effect may be greatly reduced by employing diffusing glassware and by specially designed reflectors.

The intensive carbon arc is designed to afford several advantages for interior illumination. It is essentially an enclosed arc having two upper positive carbons of small diameter and a single thick negative carbon below. A double arc is formed with a high current density which maintains the exposed ends of the positives at the highest temperature of incandescence. The light obtained is exceptionally white in color. The carbons are so fed that the arc is maintained at a definite level below a conical reflector. The light distribution obtained shows a very nearly complete concentration of light in the lower hemisphere. The specific consumption ranges from 1 watt to 1.25 watts per mean

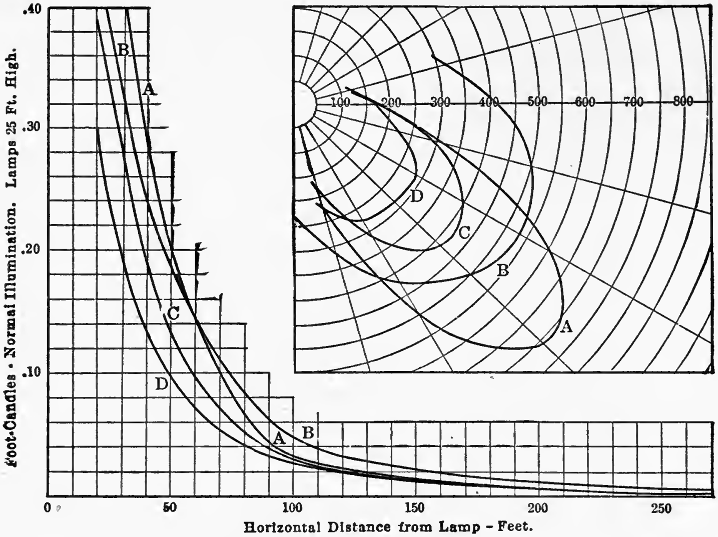


FIG. 69. Light distribution and illumination curves of typical series carbon arcs.

A. 6.6-ampere, D. C., open arc, clear globe.
B. 6.6-ampere, D. C., enclosed arc, opal inner and clear outer globe.
C. 7.5-ampere, A. C., enclosed arc, opal inner and clear outer globe, small reflector.
D. 6.6-ampere, A. C., enclosed arc, opal inner and clear outer globe, small reflector.

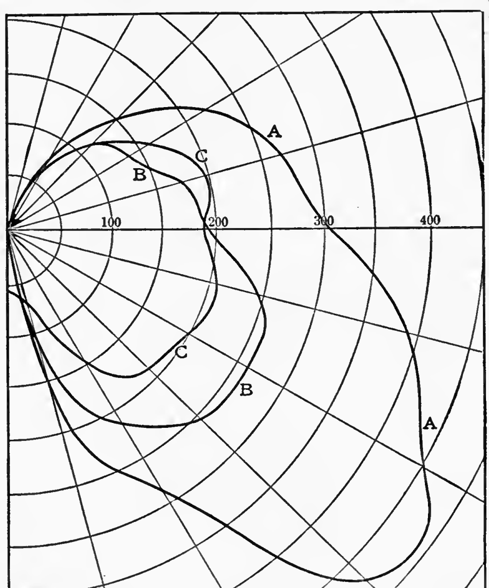


FIG. 70. Light distribution of typical multiple carbon arcs, with clear outer and opal inner globes.

A. 5.5-ampere, D. C., enclosed arc, 110 volts. B. 3.5-ampere, D. C., enclosed arc, 110 volts. C. 5.0-ampere, A. C., enclosed arc, 110 volts.

lower hemispherical candle-power, depending upon the enclosing glassware employed.

The flaming arc is representative of the second class of arc illuminants, its light being due to the luminescence of salts vaporized from intensely hot carbon electrodes. The calcium salts,

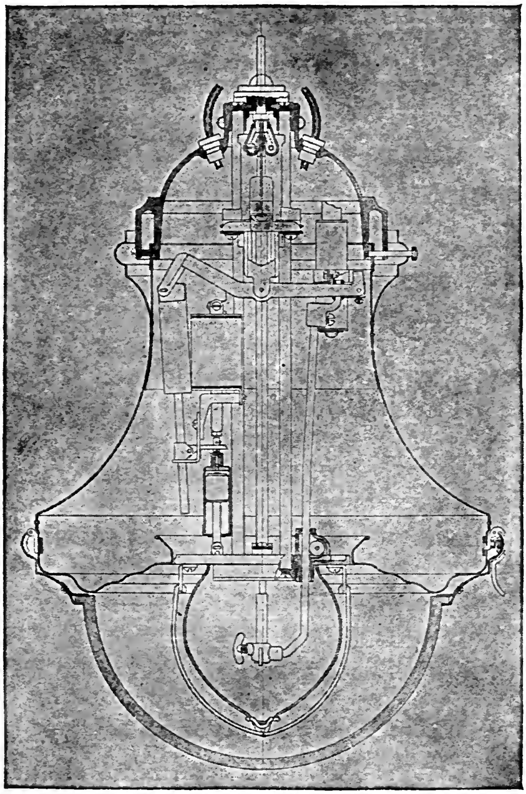


Fig. 71. — Section of intensive arc lamp.

especially calcium fluoride, yield a highly efficient yellow luminescence. Strontium salts may be employed to secure a luminescence of red color, while barium and titanium salts give brilliant white spectra. None of these salts equals calcium in efficiency. Flame arc electrodes are composed of a carbon base impregnated with luminous salts from the above group and

certain alkaline salts in addition to steady the arc and serve as flux to prevent slagging.

The precise method of light production in the flame arc is a matter of speculation. The streams of ionized vapor from both electrodes and the presence in the arc of non-ionized vapor seem to be of great importance. Luminescence is believed to result from the joint action of the anode and cathode streams and the influence of the great heat of the arc on the non-ionized vapor in stimulating luminous vibrations.

The electrical characteristics of the flame arcs closely resemble those of carbon arcs, though the potential drop at the electrodes and the arc stream resistance are reduced. The alternating-current flame arc has an inherent power factor of about 90 per cent, exclusive of that introduced by regulating reactance.

The electrodes employed in flame arcs exhibit various forms of structure. The electrodes of the Blondel system consist of several concentric cylinders of different composition, the outer one being a refractory envelope of carbon and the inner cylinders consisting of carbon mineralized to different degrees. The carbon envelope burns a little below the inner cores and thus causes them to retain the arc while protecting them from too rapid oxidation. Some makers furnish solid electrodes formed

Fig. 72. — Structure of electrodes for flame arcs.

from a homogeneous mixture of powdered carbon, luminous mineral salts and alkaline steadying salts. A third class consists of carbon cylinders having one or more longitudinal canals filled with a mineralized mixture of carbon. For use in direct-current lamps positives are generally more heavily mineralized than the negatives because of their higher temperatures, and are made of somewhat larger section to equalize the rate of burning. The size and quality of the electrodes for alternating-current lamps are the same. Very long and thin electrodes are generally formed about a fusible wire of small section, which reinforces them mechanically and increases their conductivity.

The great efficiency of the flame arc is secured at the expense of a rapid rate of electrode consumption, as the free access of air is required to carry off the fumes and smoke produced. A reasonable life per trim is secured by the use of very long electrodes or electrodes of large diameter. To still further increase the life per trim a magazine is sometimes provided which takes a charge of eight or more pairs of electrodes and cuts each pair into action when its predecessors are exhausted. The common types of flame arc electrodes are from $\frac{1}{4}$ to $\frac{3}{8}$ inch in diameter and from 16 to 24 inches in length. The rate of burning depends upon the strength of the current and varies from 1.5 to 2 inches per hour. Blondel electrodes and others of similar design are shorter and of larger diameter, with a proportionally lower rate of longitudinal consumption.

For obvious mechanical reasons the long and slender type of electrode is unsuited to vertical mounting. Fig. 73 shows the arrangement commonly employed with this class of electrodes. The electrodes are arranged in the form of a V, the base of each protruding through a central opening in a vitreous reflecting canopy. This canopy accumulates a coating of white powder from the fumes of the arc and becomes strongly reflecting. In addition it serves to deflect the fumes of the arc into draft tubes opening from its periphery and to conserve the heat of the arc. Directly above this canopy and in series with the arc is an electromagnet whose field deflects the arc downward and prevents its rising from the ends of the electrodes. The arc so formed yields a powerful and unobstructed downward light distribution.

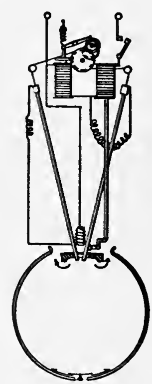


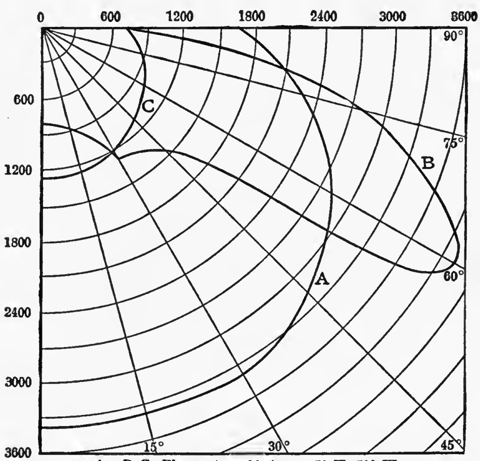
Fig. 73.—Arrangement of inclined carbon flame arc.

Inclined electrodes are employed with a variety of mechanisms, but those utilizing gravity feed are most common. In many types the electrodes are supported by inclined ways and are restrained in their feeding by an escapement clutch. One electrode is allowed a sufficient degree of lateral motion in the plane of their support to permit the arc to be drawn out to the proper length. This drawing of the arc is accomplished by a lever system operated by the plunger of a series magnet. When the voltage across the arc rises above normal by the shortening of the electrodes the shunt solenoid

releases the escapement and permits the electrodes to feed downward by gravity until equilibrium is restored.

The inclined electrode flame arc is generally operated within a single opal globe provided with air vents at the base. These vents should be so arranged that the entering air currents sweep the glass globe and prevent the deposit of a coating of sediment from the fumes. If not properly designed the lamp may have from 30 to 40 per cent of its light absorbed in such a coating.

Typical light distribution curves and operating data for inclined electrode flame arcs are shown in Fig. 74.



A - D.C. Flame Arc. 10 Amp. 50 V. 500 W. Clear Globe. 3150 M.L.H.C.P.
B - Same with Holophane Arc Shade. 2350 M.L.H.C.P.
C - Same with Opal Globe. 1070 M.L.H.C.P.

Fig. 74. — Light distribution and performance of flame arcs.

The currents most commonly employed in inclined electrode flame arcs range from 8 to 12 amperes and the voltage drop per lamp from 35 to 60. Unless operated two or three in series such arcs are adapted to 110-volt circuits only by the addition of a large ballast by which the efficiency or the power-factor is considerably impaired. The vertical arrangement of electrodes was introduced by Blondel and has been copied to a considerable extent in more recent flame arc designs. The arc is formed directly beneath a vitreous reflecting canopy or economizer, and

is maintained at a fixed height by the feeding of both electrodes. The resulting light distribution is favorable to a widespread illumination. Typical curves of distribution and performance data are given in Fig. 75.

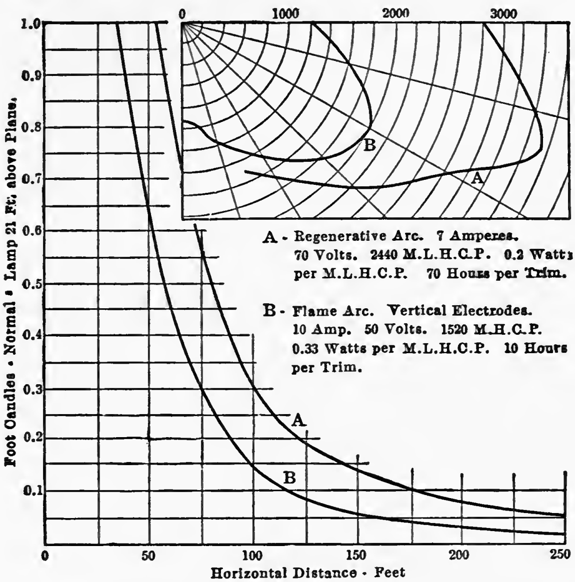


FIG. 75. — Light distribution from flame arc with vertical electrodes.

The regenerative flame arc represents the highest development of the flame arc principle, both in efficiency and long life per trim. The arc is semi-enclosed in a glass globe having two auxiliary glass tubes opening into it both above and below the arc, the arrangement being indicated in Fig. 76. A circulation of vapor is set up by the arc, the heated vapor passing around the circulating tubes from top to bottom and being used in the arc many times before finally condensing or escaping. This conserves both the heat of the arc and the vapor

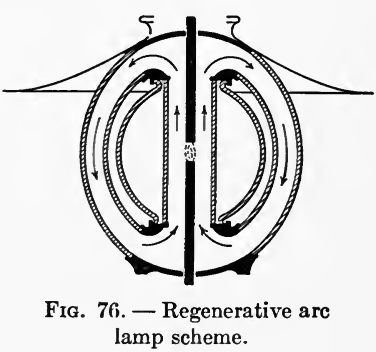


FIG. 76. — Regenerative arc lamp scheme.

supply, with a specific consumption as low as 0.25 watt per mean hemispherical candle-power and a life per trim of 70 hours, and with the advantage of wide distribution obtained from the arc between vertical electrodes.

The metallic arc and the arc formed from metallic oxides comprise the third class of arc illuminants. The anode plays an inactive role. The arc persists only so long as the ionization of the cathode is uninterrupted, and an alternating-current arc can be maintained only by a potential sufficient to form a disruptive spark after each current reversal. The metallic arc derives its spectrum entirely from the cathode material as a result of luminescence. Two arcs of this class will be considered, the magnetite arc and the mercury arc.

The magnetite arc employs as a cathode a thin iron tube closely packed with a homogeneous mixture of magnetite, titanium oxide and oxide of chromium. The iron serves as a container and gives the electrode the requisite conductivity. Magnetite vaporizes at a fairly low temperature and forms an excellent conductor in the arc. Its spectrum is but feebly luminous but is reinforced by the brilliant and efficient white spectrum of titanium oxide. The oxide of chromium restrains the vaporization of the other oxides and prolongs the life of the cathode. The anode consists of a block of copper or of brass, so proportioned that it deteriorates very slowly and requires infrequent renewal. The cathode has a life of from 160 to 200 hours, which may be still further prolonged by a sacrifice of efficiency.

The arc flame is brightest near the cathode and diminishes in brilliancy and volume as it approaches the anode. In one type of lamp the cathode is fed upward from below the anode, the arc being formed beneath a flat metal reflector which improves the light distribution. By this arrangement the slag formed at the cathode cannot fall upon the anode. In another design the cathode is placed above and fed downward. With this arrangement the air circulation about the arc must be designed with great care so that slagging is prevented. The mechanism used in series magnetite arcs is designed to feed the cathode intermittently by re-striking the arc. When the current is thrown on, the starting magnet is energized, brings the electrodes together and strikes the arc. A shunt coil

about the arc acts when the potential is sufficiently increased by the lengthening of the arc, and closes a contact which short-circuits the arc, causing the feeding coils to strike the arc anew with sufficient force to break from the end of the cathode any drops of slag which may have accumulated.

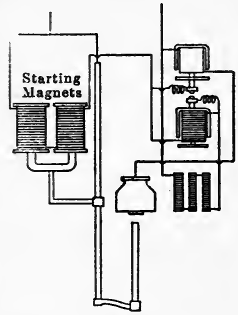


Fig. 77. — Mechanism of magnetite arc.

The magnetite arc is admirably adapted to series operation with low currents. The four-ampere lamp designed for series operation at 80 volts per lamp has had a very successful career, experience having shown it to be superior as a street illuminant to the most powerful carbon arcs. The 6.6-ampere lamp gives much greater efficiency with a somewhat shorter life per trim. The light distribution and electrical performance of typical magnetite arcs are shown in Fig. 78.

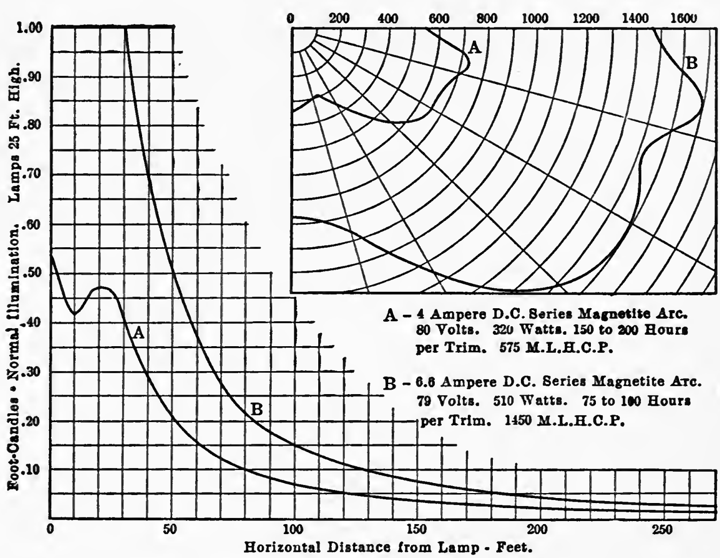


Fig. 78. — Light distribution and electrical performance of typical magnetite arcs.

TABLE X. — REPRESENTATIVE ARC LAMP DATA.

Type of Lamp.	Open or Enclosed.	Electrodes.	Hours per Trim.	Amperes.	Terminal Volts.	Arc Volts.	Terminal Watts.	Arc Watts.	Terminal Power Lac.	Watts per m. l. h. c.-p.
D.-c. series carbon arcs	Open	+Upper, solid or cored −Lower, solid	9 to 12	9.6	50	47	480	450	......	0.6
	Open	+Upper, solid or cored −Lower, solid	9 to 12	6.6	49.5	47	325	310	......	0.7
	Enclosed	+Upper, solid or cored −Lower, solid	100 to 150	6.6	72	68	475	450	......	0.9
A.-c. series carbon arcs	Enclosed	One solid One cored	70 to 100	7.5	75	72	480	450	0.85	1.25
	Enclosed	One solid One cored	70 to 100	6.6	77	72	425	400	0.85	1.35
D.-c. multiple carbon arcs	Enclosed	+Upper, solid −Lower, solid	100 to 150	5.0	110	80	550	400	......	2.25
	Enclosed	+Upper, solid −Lower, solid	100 to 150	3.5	110	80	385	280	......	2.35

A.-c. multiple carbon arcs	Enclosed	One solid One cored	70 to 100	6	110	72	430	375	0.65	2.40
	Enclosed	One solid One cored	70 to 100	4	110	72	285	250	0.65	2.60
D.-c. flame arcs	Open	Mineralized inclined	10 to 16	8	55	45	440	360	......	0.45
	Open	Mineralized inclined	10 to 16	10	55	45	550	450	......	0.40
	Open	Mineralized vertical	10 to 16	8	55	38	440	304	......	0.45
	Open	Mineralized vertical	10 to 16	10	55	38	550	380	......	0.40
Regenerative	Semi-enclosed	−Upper carbon +Lower carbon, mineralized	70	5	....	70	....	350	......	0.26
A.-c. flame arcs	Open	Mineralized inclined	10 to 16	8	55	47	374	338	0.85	0.60
	Open	Mineralized inclined	10 to 16	10	55	47	467	423	0.85	0.55
	Open	Mineralized vertical	10 to 16	10	55	40	467	360	0.85	0.55
Magnetite	Open	+Copper −Metallic oxide	150 to 180	4	80	78	320	312	......	0.70
	Open	+Copper −Metallic oxide	70 to 100	6.6	80	78	528	515	......	0.45

NOTE. — Values of watts per m. l. h. c.-p. approximate for open carbon arcs and magnetite arcs with clear globes, enclosed carbon arcs with opalescent inner and clear outer globes, and for flame and regenerative arcs with opal globes.

The magnetite arc is essentially a direct-current lamp. Its high efficiency and long life per trim may be combined with the advantages of alternating-current generation and distribution by the use of a rectifier to convert the energy into a unidirectional current. A very effective combination of mercury arc rectifier and constant-current transformer has been developed for this

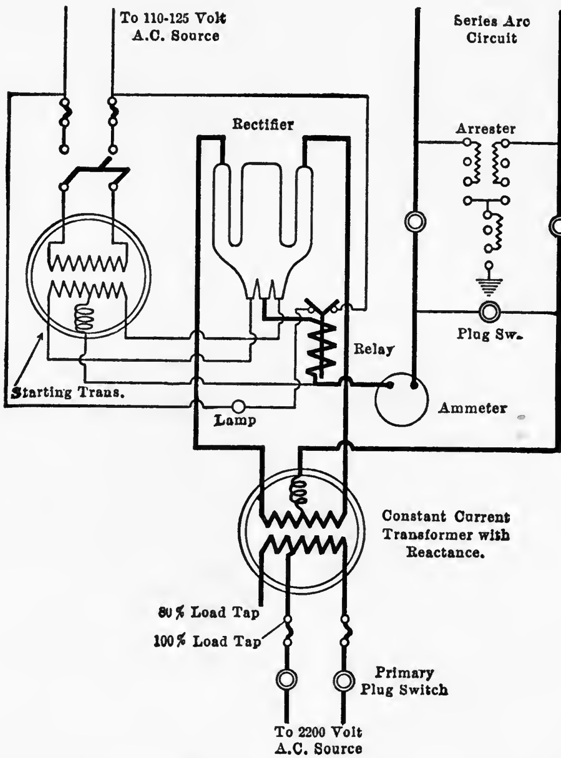


FIG. 79. — Circuits of transformer set for magnetite arc operation.

purpose. The general scheme of the set is indicated in Fig. 79. The set is contained within a single iron case provided with facilities for air or oil cooling. The rectifier tubes have an average life of about 900 hours. The magnetite arc is also furnished for constant-potential operation equipped with a reflector which gives a form of light distribution suitable for interior illumination.

The mercury arc exhibits all the characteristics of a true metallic arc. It is essentially a direct-current arc derived from the electro-vaporization of a mercury cathode. The anode may be iron, graphite or any conducting material not attacked by mercury. The arc is formed in an evacuated glass tube, supported in an inclined position with the cathode chamber at the base. The vapor condensing at the anode chamber at the top of the tube is returned to the cathode by gravity. The final failure of the tube results from the loss of vacuum rather than from the exhaustion of mercury.

The electrical characteristics of the mercury arc so formed differ from those of other arcs in that the arc is not free to expand and undergoes a change in the vapor density with the current. The effect of this change is shown in the volt-ampere characteristic, Fig. 80, from which it may be seen that the con-

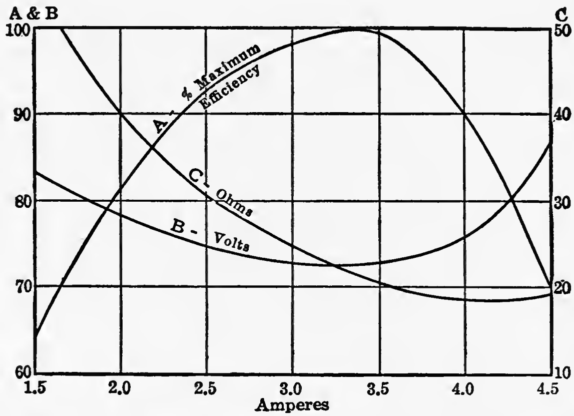


Fig. 80. — Volt-ampere, resistance and efficiency characteristic of the mercury arc lamp.

ductivity of the arc is unstable below a certain critical current and stable for all higher values. As the highest luminous efficiency is secured close to this critical point it is desirable that the lamp be operated but slightly beyond it. This may be safely done when the lamp is provided with a series ballast of resistance and inductance to compensate for variations of the line potential.

When in operation the potential drop at the anode is approxi-

mately constant at eight volts and the cathode drop at five volts, the potential fall in the arc column being proportional to its length and vapor density. In starting the lamp the cathode must be excited to a state of ionization. This may be accomplished either automatically or manually by tilting the lamp and so bringing the electrodes into metallic contact. As the stream of mercury is ruptured the arc is struck and quickly fills the tube. The cathode may also be excited by passing a high-potential spark discharge through the tube. This is accomplished automatically in lamps of recent design by a "shifter" or electromagnetically operated mercury switch which causes an inductive coil to discharge through the tube.

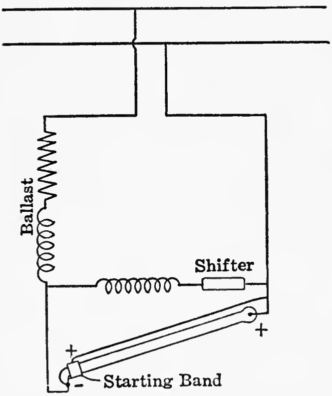


Fig. 81. — Diagram of connections of automatic starting mercury arc.

The light of the arc is produced by the electro-luminescence of the mercury vapor. It is a characteristic mercury spectrum consisting of three bands of yellow, green and violet respectively. The absence of red from its spectrum disqualifies the mercury arc from service where accurate color discrimination is essential. Attempts to remedy this defect by the addition of other metals to the mercury have not met a practical success. Some degree of color balancing is often obtained by enclosing a mercury arc and low efficiency carbon lamps in the same globe, the resulting light being of a fairly satisfactory color, and the combined efficiency high enough to warrant the expedient. The light of the arc is of strong actinic qualities and is valuable for its exceptional power of revealing fine details. Its intrinsic brilliancy is very moderate, approximately 17 candle-power per square inch, and the diffused nature of the light tends to the elimination of shadows, even in the presence of obstructions. These qualities give the mercury arc a special value for certain classes of service.

Although essentially a direct-current arc it may be adapted to operation from alternating-current lines by the use of the principle of the mercury arc rectifier. The accompanying dia-

gram indicates the necessary connections. The tube is provided with two distinct anodes, each connected to one of the supply mains. Bridged across the mains is an inductive coil to the middle point of which connection is made from the cathode through a suitable inductance and resistance. The anodes alternately become positive with respect to the cathode and each serves to carry the arc during the corresponding half cycle. The inductance assists in carrying the arc over the zero points in line pressure and renders the rectified current more uniform.

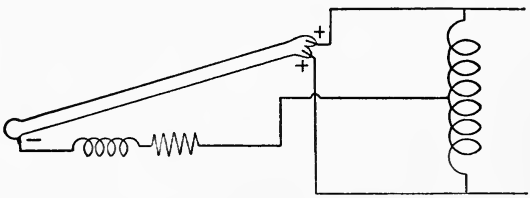


Fig. 82. — Alternating-current mercury arc lamp.

The photometry of the mercury arc is rendered difficult and complex by the unusual color value and dimensions of the light source. At ordinary distances the law of inverse squares does not apply to the case, hence values of candle-power and efficiency can be considered as approximate only. The form of the light distribution curves obtained from such lamps is dependent upon the distance at which the observations are taken. Such curves are of slight value in the practical design of illumination systems. The principal data relating to the commercial forms of mercury arc are given in Table XI.

TABLE XI. — COMMERCIAL DATA ON MERCURY ARC LAMPS.
(Cooper Hewitt.)

Type of lamp.	Kind of circuit.	Length, inches.	Volts.	Current, amp.	Watts.	Hemisph. c.-p.	Watts per candle.
H	d. c.	20¾	52–55	3.5	177–193	300	0.64
K	d. c.	45	100–120	3.5	350–420	700	0.55
U	d. c.	78	206–240	2.0	412–480	900	0.48
P	d. c.	50	100–120	3.5	350–420	800	0.48
F	a. c.	50	100–120 200–240	......	400–520	750–900	0.53–0.58

When type H lamps are to be connected to 110-volt circuits the operation of the lamps two in series is necessary for the best efficiency. To permit this the housing of each lamp contains a resistance equal to the normal operating resistance of the lamp. When the lamp is not in operation the circuit is completed through this resistance, permitting the operation of either lamp independently. This resistance is automatically cut out when the lamp is thrown on. Fig. 83 indicates the connections employed.

The efficiency of the mercury arc as an illuminating device may be nearly doubled by placing over the tube a dihedral

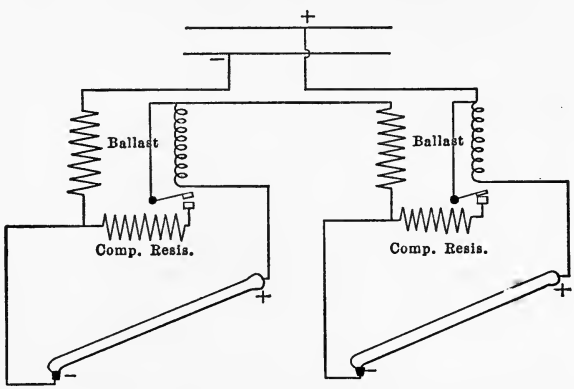


Fig. 83. — Connections for the operation of two type H lamps in series.

reflector of white matt surface. By such an arrangement a specific consumption equivalent to 0.31 watt per mean hemispherical candle-power may be obtained. The tubes have a life of approximately 1000 hours, rendering the maintenance cost low.

The high-pressure mercury arc has been developed in Europe but has not been commercially applied in America. It operates at a vapor pressure greatly in excess of the common type and acquires a temperature so great that a quartz tube must be substituted for the familiar glass tube. The arc is of small dimensions, the 110-volt lamp being about 8 centimeters long and from 1 to 1.5 centimeters in diameter. Its light is of great intensity and has a better balanced spectrum than the common mercury arc, due to the presence of red rays. A specific consumption of 0.25 watt per candle-power is obtained.

The Moore vacuum tube applies the principle of the Geissler tube discharge to commercial lighting. It consists essentially of a highly evacuated glass tube about 1¾ inches in diameter and of any desired shape and length up to 200 feet. A pair of graphite electrodes sealed into the ends of the tube are attached to the secondary terminals of a high-potential step-up transformer. When in operation the electrical discharge through the column of rarefied gas causes it to luminesce and glow with a soft and highly diffused light, the intrinsic brilliancy being about 0.66 candle-power per square inch when in normal operation. The color of the light so obtained is dependent upon the nature of the gas within the tube and admits of ready control. The spectrum of diffused white daylight is closely reproduced when carbon dioxide is employed. Nitrogen may be used to secure an orange tinted light of higher efficiency. Air yields a light of pinkish tint.

The conductivity of the tube reaches a maximum at a critical pressure of 0.08 millimeter of mercury, but the maximum luminous efficiency obtains at a pressure between 0.10 and 0.12 millimeter. The continued operation of the tube tends to a gradual reduction of the pressure due to the formation of a solid precipitate from the gas. A feeder valve is provided to compensate for this loss and to regulate the pressure to the most efficient value. This valve consists of a plug of porous carbon cemented into the end of a small glass tube communicating with the main tube. This plug is normally immersed in mercury. As the gas pressure falls below the normal value and approaches the critical point the conductivity of the tube rises and causes an increased flow of current in the primary circuit. A solenoid is thus strengthened and attracts its plunger which lifts a glass displacer from the mercury and lowers its level, exposing the tip of the carbon plug until the inward leakage of gas has restored the pressure within the tube to the normal value. The details of the feeder valve are shown in Fig. 84. The arrangement of the terminal box within which the transformer, the feeder valve and the terminals of the tube are contained is indicated in Fig. 85.

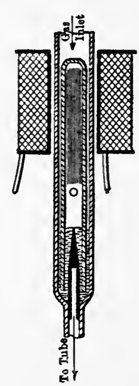


Fig. 84. Feeder valve for Moore vacuum tube.

The chief operating characteristics of the tube are indicated in Fig. 86. The relatively low power-factor inherent in the system is a manifest disadvantage as it is not practicable to raise its value above 85 per cent and commercial installations operate at still lower values. The efficiency of the tube when filled with nitrogen competes with that of metal filament and Nernst lamps. The tubes are made up in place by welding together short lengths, the completed tube being suspended from the ceiling or supported by the walls of the room. The tubes are claimed to have a life equal to several years of ordinary operation and the renewal cost

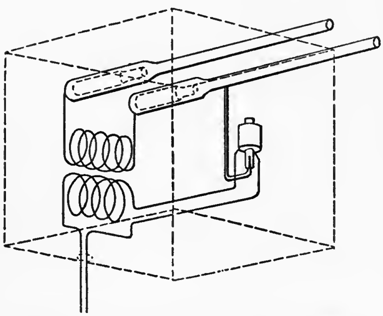


Fig. 85. — Terminal box for Moore vacuum tube.

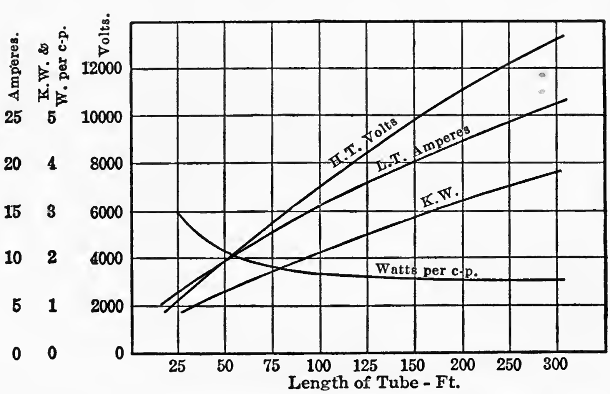


Fig. 86. — Operating characteristics of Moore vacuum tube.

is moderate, so that the maintenance charges on the system are very low. The commercial use of the system has been comparatively small. Its most noteworthy feature is the possibility of reproducing the quality and spectrum of diffused daylight, in which it stands alone among modern illuminants.

CHAPTER XI.

ILLUMINATION BY GAS.

It is the purpose of this chapter to set forth a brief résumé of the salient principles of gas lighting. For detailed information the reader is referred to the standard literature of gas engineering.[1]

Qualities of gas.—The value of gas for lighting is largely determined by two qualities, viz., its *calorific value*, measured in British thermal units per cubic foot, and its *illuminating power*, measured by the intensity of the flame of a standard burner consuming five cubic feet per hour, the quantity of gas in each case being referred to a standard temperature of 60 deg. fahr. and a barometric height of 30 inches. Fully 90 per cent of the gas commercially supplied is used primarily for its heating effects in stoves or in incandescent illuminating devices. The prevailing methods of gas production do not render it feasible to supply gas of high heat value which is seriously deficient in illuminating power, hence it is usually sufficient to govern only the calorific value of gas by ordinance or specification.

The luminous properties of the gas flame are due to the liberation in a highly heated zone of minute particles of carbon which glow with incandescence until oxidized or carried from the zone of action as smoke. When gas is fully aërated before combustion the luminous effect is prevented by the rapidity of oxidation. The luminous properties of a gas are dependent upon the quantity and the richness of the hydrocarbon vapors in its composition, though there is no simple proportionality between the two. Table XII indicates the chemical formulas, the calorific value and the illuminating power of the most valuable hydrocarbons, known technically as illuminants: —

[1] Much of the matter here given is based upon a paper by Fulweiler. See Trans. Ill. Eng. Soc., Vol. IV, p. 65.

TABLE XII. — ILLUMINATING VALUE OF HYDROCARBONS.

Gas.	Formula.	Gross B.t.u.	Candle-power.
Methane	CH_4	1009.0	5.2
Ethane	C_2H_6	1764.4	35.7
Ethylene	C_2H_4	1588.0	70.0
Acetylene	C_2H_2	1476.2	210.0
Benzol	C_6H_6	3807.5	420.0
Toluol	$C_6H_5CH_3$	....	741.7
Naphthalene	C_8H_{10}	....	900.0

The calorific value of gas is directly dependent upon its composition. In addition to the above hydrocarbons the following non-luminous constituents are found in commercial gas and contribute to the heating value in the proportions indicated: —

Hydrogen, H..................326.2 B.t.u. per cubic foot.
Carbon Monoxide, CO..........323.5 B.t.u. per cubic foot.

In referring to the calorific value of a gas distinction is made between the gross value, or the total heat of combustion, and the net value, or the communicable value as measured by a calorimeter.

Manufacture of Commercial Gas.

Coal gas is the product of the distillation of gas coal. The process is carried on in externally heated closed retorts from which the impure gas is led off through washers, scrubbers and purifiers where it is separated from its impurities and by-products, and finally delivered to storage tanks. It is not a simple gas but rather a mixture, of which the most valuable components are hydrogen, carbon monoxide, methane and illuminants. Its illuminating power is generally between 15 and 18 candles, unless increased by carbureting, and its calorific value approximates 650 B.t.u. It is of historic interest as having been the medium of the early development of the gas industry. Owing to the increasing scarcity of gas coal its commercial importance is declining.

Water gas consists mainly of a mixture of hydrogen and carbon monoxide, generated by decomposing steam in the pres-

ence of incandescent carbon, and enriched by the addition of illuminants. The essential steps of the process are as follows: — (1) The three main chambers, viz., the generator, containing a bed of coal or coke, the carburetor, containing a checkerwork of fire brick, and the superheater, are preheated by blowing an air blast through the fuel bed. The fuel is raised to incandescence and gives off a producer gas whose further combustion is utilized to heat the carburetor and the superheater. (2) The air blast is cut off and a steam blast substituted, resulting in the following reactions in the generator: —

$$C + 2\,H_2O = 2\,H_2 + CO_2$$
$$C + CO_2 = 2\,CO.$$

(3) The resulting gas with its by-products passes into the carburetor, meeting a spray of oil which is vaporized as it passes down through the heated checkerwork with the column of gas. (4) The gas thus enriched passes into the superheater where the hydrocarbon vapors are *fixed* by the high temperature to prevent their subsequent recondensation. (5) The gas is then purified and cleaned, then stored in tanks under suitable pressure. The candle-power and calorific value of the gas depend upon the degree of its enrichment. Water gas produced by such a process constitutes the bulk of the artificial gas supply of American cities.

Oil gas is derived from the distillation of hydrocarbon oils at a temperature sufficient to " crack " the oil into vapors which are stable in the gaseous state. Oil gas is often of such a degree of richness as to render its efficient combustion difficult, hence it is sometimes diluted before distribution. Oil gas is subject to deterioration from the condensation of some of its heavier hydrocarbons. Pintsch gas, which is used extensively for train lighting, is an oil gas which is stored in small tanks under heavy pressure, rendering a sufficient supply for a long run easily transportable. Otherwise oil gas is of diminishing importance.

Acetylene is a simple hydrocarbon gas, C_2H_2, produced commercially by the reaction of water and calcium carbide, thus: —

$$CaC_2 + 2\,H_2O = Ca(OH)_2 + C_2H_2.$$

Acetylene aërated in certain proportions is a dangerous explosive but the odor of certain of its common impurities renders its escape easily detected. The expense of calcium carbide is such

as to limit the field of acetylene largely to isolated installations and to portable lamps with self-contained generators.

Natural gas is derived from wells sunk to great depth in the earth and frequently occurs in connection with crude petroleum. It is especially rich in methane and burns with a hot but feebly luminous flame, which limits its application to lighting to use with incandescent lamps.

Typical analyses of common varieties of gas are given in Table XIII.

TABLE XIII. — TYPICAL ANALYSES OF COMMON VARIETIES OF GAS.

	Coal gas, per cent.	Water gas, (fuel), per cent.	Water gas, (enriched), per cent.	Oil gas, per cent.	Natural gas, per cent.
Hydrogen	46.0	48.0	40.0	32.0	3.0
Methane	40.0	2.0	25.0	48.0	92.0
Carbon monoxide	6.0	38.0	19.0	0.0	0.0
Carbon dioxide	0.5	6.0	3.0	0.0	0.0
Nitrogen	2.0	5.5	4.0	2.0	2.0
Oxygen	0.5	0.5	0.5	0.5	0.0
Illuminants	5.0	0.0	8.5	16.5	3.0
B.t.u.	665	300	585	850	935

Gas Flames.

Two general types of gas flames may be noted, the luminous and the Bunsen or non-luminous flame. Each type of flame consists of two zones, as indicated in Fig. 87. The outer zone *abc* of the luminous flame consists of a non-luminous envelope of hydrogen, methane and carbon monoxide in a state of rapid combustion. Within this highly heated envelope and protected by it from rapid oxidation are the heavier and less diffusive hydrocarbons. These are decomposed upon reaching a temperature of about 1200 deg. cent. and liberate incandescent particles of carbon which continue to glow with incandescence until consumed or carried away as smoke.

The non-luminous or aërated flame of the Bunsen burner also shows two zones. The inner and lower is a conical bluish green zone at a temperature of approximately 1550 deg. cent. resulting from the explosive reaction between the gas and the entrained

air. The size, color and stability of this zone depend upon the degree of aëration of the gas. Over-aëration may lead to a flash back, the gas igniting at the base of the Bunsen tube. The

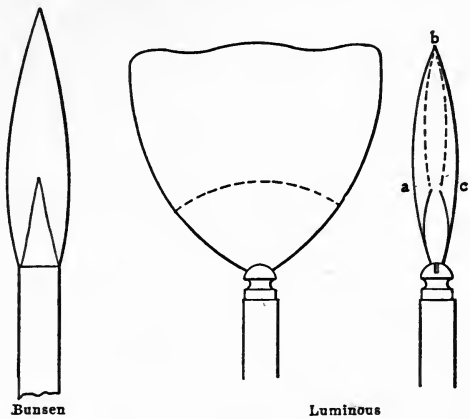


FIG. 87. — Sections of gas flames.

outer envelope surrounding and surmounting the inner zone is the region of oxidation and has a temperature approximating 1800 deg. cent. The latter zone is entirely non-luminous.

Open Flame Burners.

The flat flame burner consists of a steatite tip tightly fitted to the upper end of an upright brass cylinder. The tip of the *fishtail* burner is concave and has two small orifices so inclined that the two jets of gas impinge upon each other and spread out into a broad flat flame. Because of the tendency of these holes to become clogged with soot the fishtail tip has largely given way to the familiar *bat's-wing* burner, consisting of a steatite dome with a narrow gas slit.

The argand burner, now little used except as a standard burner in gas testing, consists of a hollow steatite ring with its upper surface perforated with a circle of small holes from which the gas issues as a cylindrical flame. The flame is surrounded by a cylindrical glass chimney. The draft inducing action of the chimney brings air into contact with both sides of the flame, the whole arrangement being such as to promote the most efficient and uniform combustion of the luminous order.

The regenerative burner is so constructed that the waste heat of combustion is utilized to pre-heat the gas and air supplied to the flame, minimizing the convection losses and so improving the efficiency.

The illuminating duty of any burner increases with the pressure of the gas up to a certain point when the flame is just short of smoking, but falls rapidly with a further increase of pressure. The most effective pressure for any burner depends upon the quality of the gas supplied. Flat flame burners rated at 4 cubic feet per hour yield a duty of about 2.5 candles per cubic foot; 5-foot burners give from 2.75 to 3 candles per cubic foot; well-

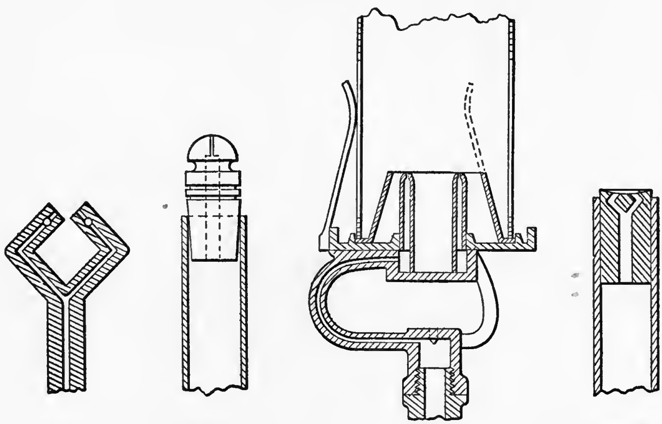


Fig. 88. — Sections of luminous flame burners.

adjusted argand burners from 3 to 3.5 candles per cubic foot and regenerative burners a duty about three times this amount, 16-candle gas being taken as the basis of these estimates. Acetylene is commonly burned in a special duplex burner quite similar in action to the fishtail type. Mantle burners of special design have been employed with acetylene and yield a very high duty.

Incandescent Gas Illuminants.

Incandescent mantles.—The basic idea of an incandescent illuminant heated in the Bunsen flame was evolved as early as 1826, but was not developed to the practical stage until Dr. Auer von Welsbach first brought out his mantles in 1886. Auer discovered that the ashy residue derived from burning a cotton

fabric saturated with a solution of rare earth oxides possessed remarkable refractoriness, strength and luminous properties. His early mantles were made from a mixture of lanthanium and zirconium oxides. They were not highly efficient and gave a very short life. Auer's discovery of the effectiveness of the 99 per cent thoria and 1 per cent ceria combination in 1892 paved the way to a brilliant success. Very conflicting theories have been advanced to account for the high luminous efficiency of the thoria-ceria combination. The best evidence indicates that thoria alone is a poor radiator and is capable of maintaining a high temperature, but is inefficient in the production of light. Ceria possesses remarkable radiating power but can not alone maintain the high temperature requisite for efficient luminosity. A combination of the two in which the ceria is in a finely divided state is able to maintain a high temperature and give a highly efficient light emission. The ceria is often termed an excitant oxide. Other combinations of oxides are known to be still more efficient but practical considerations prohibit their commercial use.

The mantle passes through the following steps in its manufacture. A long tubular fabric is knitted from carefully selected cotton thread. This fabric is cut into suitable lengths and uniformly impregnated with a "lighting fluid" containing the thoria-ceria combination. When the mantle is dry one end is carefully plaited and threaded through with an incombustible supporting thread of asbestos. After being molded to the proper shape the mantle is hung on a hook and ignited and the thread burns out to a flabby ash impregnated with the active oxides. The mantle is then blown out to size, dipped in collodion to lend it ruggedness in shipment, trimmed to its final size and packed. Great skill and care are required at all stages of the process.

The quality of a mantle is determined very largely by three factors, viz., its initial light-giving capacity, its mechanical strength and its ability to maintain both the quality and the quantity of its light through a satisfactory period of life. These factors are dependent upon the quality of the fabric employed, the quality and purity of the lighting fluid and the degree of skill exercised in all the steps of manufacture. The importance of the standardization of mantles upon the basis of their efficiency

and life as illuminants has had but little commercial recognition. In the matter of mechanical durability, however, some degree of rating has been maintained. The quality of the light derived from mantles is a matter of much dispute, founded often upon prejudice both favorable and hostile. The efficiency of the mantle is due in large part to the selective emphasis of the highly luminous yellow and yellowish green rays in its spectrum, the red element being less pronounced than in other common sources of artificial light. The greenish tinge of the light grows more prominent as the mantle ages, especially in the poorer grades. Spectrophotometric tests of high grade mantles taken in their early life show a very satisfactory color composition.

The general conditions to be met to secure from mantles their best efficiency may be briefly summarized as follows. First of all, the mantle should be of good quality as regards both its luminous and mechanical properties. When operating it should be entirely enveloped in the hottest zone of a non-luminous flame and supplied at a constant pressure with a gas-air mixture so proportioned as to give the hottest flame consistent with stable combustion. The mantle and flame should be surrounded with a cylindrical chimney whose dimensions and draft-inducing power are best adapted to the nature and size of the flame. The luminosity secured depends upon the temperature of the mantle, which in turn is dependent upon the calorific value of the gas, the velocity of its projection and the degree to which the positions of the mantle and the hottest zone coincide. The illuminating duty obtained may be greatly increased by pre-heating the air and gas supply on the regenerative principle.

The efficiency and intensity of the light from a mantle are greatly affected by the pressure of the gas supply. The curve in Fig. 89 is illustrative of these relations. With the increase of pressure the more rapid velocity of the gas increases the temperature of combustion and lessens the difference between the flame temperature and that of the mantle. In certain self-intensifying systems the waste heat of the ascending products of combustion is utilized to operate a small compressor by which the pressure of the gas or the gas-air mixture is raised before combustion, resulting in a greatly increased illuminating duty.

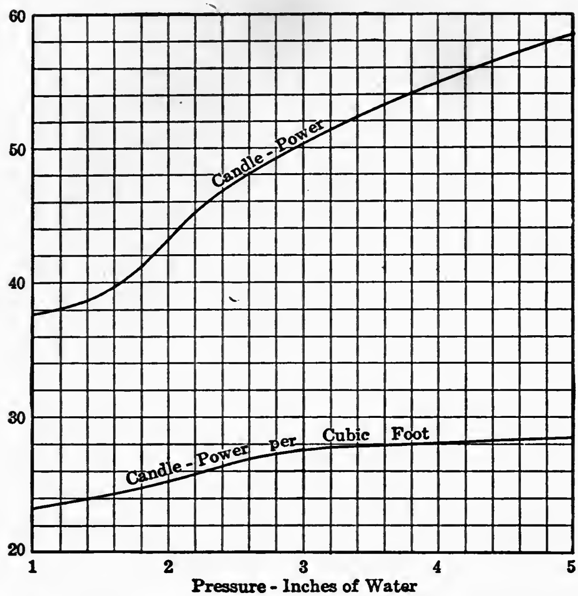


FIG. 89. — Dependence of mantle efficiency and intensity upon supply pressure.

Incandescent Burners.

The burners employed with incandescent mantles are of two general types, the upright and the inverted, each consisting of a Bunsen burner developed to meet special technical requirements. Detailed descriptions are not here attempted owing to the great variety of construction.

The essential parts of the upright burner and their functions are: (1) A constricted gas orifice from which the gas issues with sufficient projection to produce a flame fully enveloping the mantle; (2) adjustable air ports through which air is entrained by the injector action of the gas; (3) a vertical Bunsen tube to assist the injector action; (4) a mixing chamber in which the gas and air are intimately mixed; (5) a fine wire gauze between the mixing chamber and the flame to prevent flash backs; (6) a gallery for the support of the chimney; and (7) a properly proportioned chimney whose draft supplies the external air supply of the flame.

The inverted burner is designed to meet more complex conditions. The low specific gravity of the gas renders its downward projection difficult, hence its path from the orifice to the flame should be made as straight and unobstructed as possible. The air ports must be carefully protected from the products

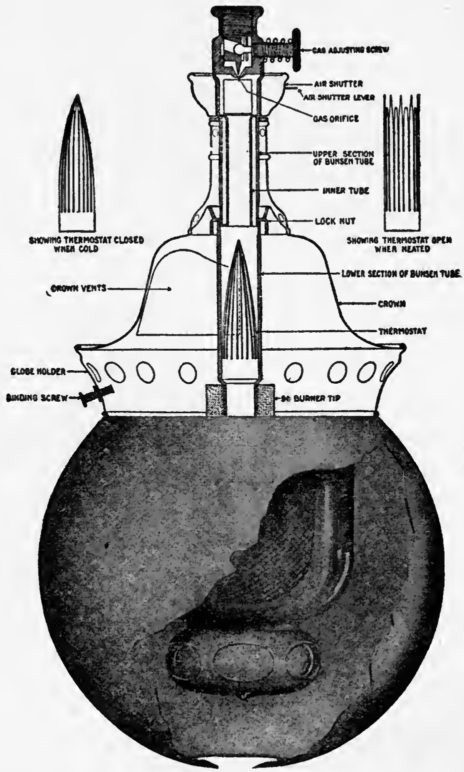


Fig. 90. — Sectional view of an inverted burner.

of combustion. The Bunsen tube becomes heated by the ascending gases and undergoes a loss of entraining power. If the ports are properly adjusted for the initial stages of operation the air supply soon besomes inadequate and results in poor combustion; if the ports are properly adjusted for the final stages the initial air supply is excessive and may lead to a flash back. The structure of all the parts exposed to heat must be refractory and free from liability to corrosion.

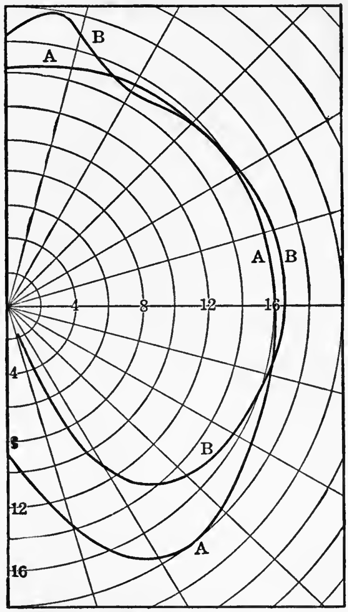
In one of the most successful designs the regulation of the air supply is accomplished by a thermostatic valve in the form of a slitted cone mounted in the mixing chamber. When cold the cone is partially closed and reduces the entraining capacity. As it becomes heated its fingers open flat against the walls of the tube, removing all obstruction and raising the entraining power to the proper value. The disadvantages and complications of the inverted burner are quite offset by the increased efficiency resulting from its regenerative action and by the unobstructed downward distribution of light.

The gas arc lamp borrows its name from the electric arc and is designed to resemble it in its simplicity of maintenance, light distribution and intensity, the quality and concentration of its light and the simplicity of its ignition. The gas arc consists of a cluster of upright mantles surrounding a central gas supply tube, each burner having its adjustable gas check and air ports, but the whole system controlled from a single cock. Automatic ignition is usually accomplished by a small pilot flame which burns continually but which is caused to flash up by an added puff of gas when the main cock is opened. A valuable turn-down feature is added in many indoor arcs by giving the cock three positions, all burners being ignited when the cock stands at the on-position, all but the pilot burner being extinguished when at the off-position and a single night burner being in operation when at the neutral. The cluster is surrounded by a pear-shaped glass globe, which may be of clear glass or diffusing glass as desired, and which opens at its upper end into a brass chimney or draft inducer.

Light Distribution and Efficiency of Gas Illuminants.

It is impossible to give definite information concerning the light distribution and efficiency of gas lamps as the number of variables encountered is too great. The data given in Figs. 91 to 94 are therefore to be regarded as illustrative, though it is believed to be fairly typical of the best standards of performance.

The hygienic aspects of gas lighting have received much distorted and prejudiced comment. The products of combustion are water vapor and carbon dioxide, both of which are without danger except as they tend to dilute the atmosphere of the



A - Ordinary Open Flame.
B - Argand Burner.

FIG. 91. — Light distribution from open gas flame burning 5 cu. ft. per hour.

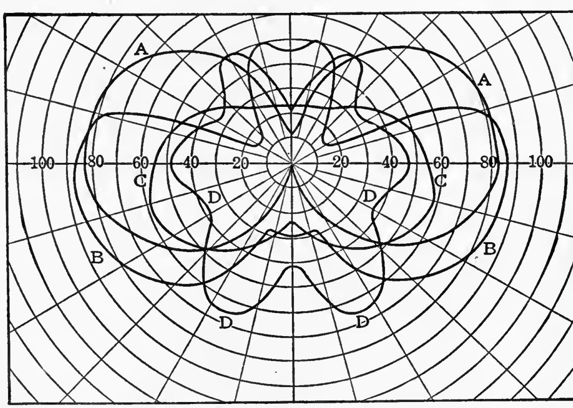


FIG. 92. — Light distribution from upright incandescent mantle burners.[1]

A. Bare upright mantle, 3.7 cu. ft. per hour at 1.6 inches pressure.
B. Mantle burner with fluted white reflector, 3.7 cu. ft. per hour at 1.6 inches pressure.
C. Mantle burner in opal Q globe, 5 cu. ft. per hour at 1.5 inches pressure.
D. Mantle burner in Holophane Class A shade, 3.55 cu. ft. per hour at 1.25 inches pressure.

[1] Cravath and Lansingh: Practical Illumination, p. 82.

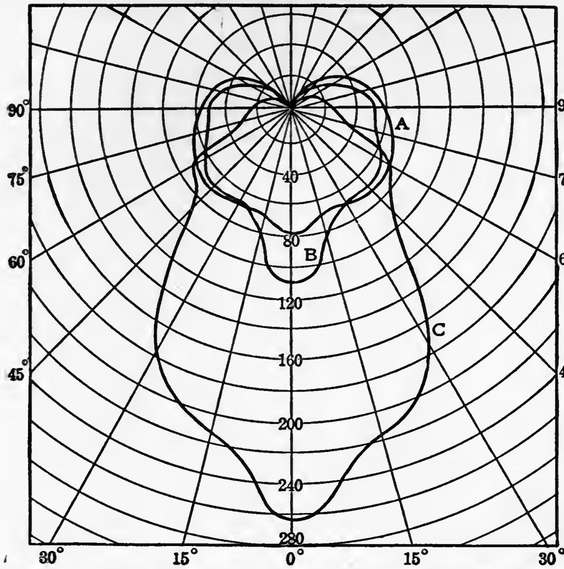


FIG. 93. — Light distribution from inverted mantle burner.[1]

A. Bare inverted mantle, 3.0 cu. ft. per hour, 1.5 inches pressure.
B. Same with ground-glass ball.
C. Same with holophane reflector.

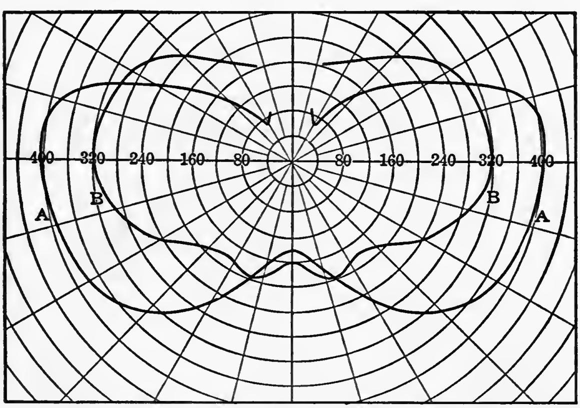


FIG. 94. — Light distribution from gas arcs.

A. Four mantle gas arc with clear globe and flat porcelain reflector, 21 cu. ft. per hour at 1.5 inches pressure.
B. Four mantle gas arc with alabaster globe, 22.5 cu. ft. per hour at 1.5 inches pressure.

[1] Cravath and Lansingh: Practical Illumination, p. 90.
[2] Cravath and Lansingh: Practical Illumination, p. 128.

room. A certain degree of vitiation of oxygen is to be expected and the liberation of heat is unavoidable, but the ill effects of these processes are largely offset by the ventilation currents induced by the flame action. In poorly ventilated rooms the products of combustion may cause a slow discoloration of wall paper and contents. Open flame burners sometimes operate poorly and give out smoke and soot, but only under abnormal conditions. Dangers from the escape of gas such as asphyxiation and explosion are slight, due to the ease with which the odor of escaping gas may be recognized.

Much of the progress of the gas lighting industry is due to the pressure of wholesome competition with the electrical industries. The evidences of such progress are to be seen in the development of artistic fixtures, illuminants with a favorable inherent light distribution, the production of low intensity illuminants of high efficiency, and the development of automatic ignition systems operated on the pilot lamp principle and by the spark from an electrical induction coil.

CHAPTER XII.

ACCESSORY DEVICES FOR ILLUMINANTS.

Few of the primary sources of artificial light are inherently well adapted in the quality and the distribution of their light to give the most effective service. Their intrinsic brilliancy is far too high for eye comfort and a large proportion of the light is generally given off in directions where it is of little direct value. Diffusers and reflectors are intended to fulfill the following functions, viz., (1) to soften the light by increasing the apparent luminous area; (2) to redirect such rays as would otherwise be ineffectively used; (3) to improve the spectrum by the absorption of colors present in excess and (4) to add decorative value. Some devices combine these functions most effectively, others are intended to fulfill but one, while others fail in all, through poor design and improper use.

First-class diffusion is secured when the intensity of an illuminant is uniformly reduced to two candle-power per square inch or lower. Table XIV of estimates of the inherent intrinsic

TABLE XIV. — INTRINSIC BRILLIANCY OF LIGHT SOURCES.

Moore vacuum tube	.60	Carbon filament lamps	300–500
Frosted incandescent lamps	2.00–6.00	Gem lamp	625
Candle flame	2.00	Tantalum lamp	750
Bat's-wing gas flame	2.26	Tungsten lamp	1,000
Mercury arc	16.7	Nernst glower (bare)	1,000
Incandescent gas mantle	20–25	Flame arc (bare)	5,000
Enclosed carbon arcs	75–500	Open d. c. arc crater	200,000

brilliancy of various primary light sources emphasizes the need of careful attention to diffusion. Partial diffusion is obtained when the primary source is still visible through the shade. Uniform diffusion better meets the needs of vision, but is generally accompanied by greater light absorption. Shades for metal filament lamps and arcs used in interior lighting should be so designed as to entirely conceal the primary source.

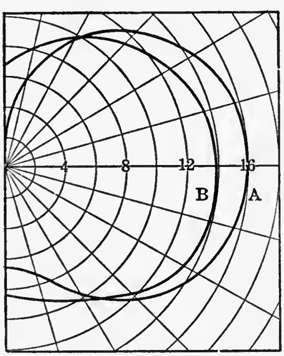
The commonest diffusing media are (1) ground glass, prepared from clear glass by either acid etching or sand-blasting one surface, (2) alabaster glass, recognizable by its pale bluish tint, (3) opalescent and opal glass which owe their diffusing power to finely pulverized opaque particles held in suspension, and (4) prismatic glass in which diffusion is secured by the diffraction of light. The absorbing power of these materials is estimated in Table XV. The loss of considerable light by

TABLE XV. — ABSORBING POWER OF VARIOUS GLASSES.

Kind of glass.	Per cent.	Kind of glass.	Per cent.
Prismatic glass	12 to 15	Ground glass	18 to 30
Light sand-blasted glass	12 to 20	Opalescent glass	25 to 40
Light alabaster glass	15 to 30	Heavy opal glass	30 to 60
Heavy alabaster glass	25 to 40		

absorption is not too great a price to pay for the benefits of good diffusion, since the eye adjusts itself for the brightest object in the field of view and others are apt to be indistinct by contrast, even though amply illuminated.

Reflecting surfaces may be grouped into three classes, diffusing, regular and prismatic. Diffuse and regular reflection are usually found simultaneously from porcelain, opal glass and enameled metal. Mirrored and polished metal reflectors give a pronounced regular reflection. Opal glass surfaces may be rendered diffusely reflecting by careful treatment to remove all surface glaze. Prismatic reflectors are ribbed with totally reflecting prisms. The edges and grooves are slightly rounded, allowing the transmission of sufficient light to produce a moderate illumination of the upper surfaces of the room. Opal reflectors also transmit a moderate amount of light.



A - Bare 16 C.P. Lamp.
B - Same in 6 in. Ground Glass Ball.

FIG. 95.

The result of enclosing any illuminant in a non-prismatic diffusing globe is to render its light distribution more uniform. Fig. 95 shows the effect of a 6-inch sand-blasted ball upon the dis-

tribution of a 16 candle-power incandescent lamp. Prismatic globes may be designed to give a wide variety of distribution curves from a given enclosed illuminant, the results depending upon the refracting properties of the prisms. The external prisms are ribbed horizontally, the contour depending upon the light distribution desired. The inner prisms are ribbed vertically, the two sets combining to produce perfect diffusion. The control of the designer over the light distribution obtained is illustrated by the curves of Fig. 96, referring to

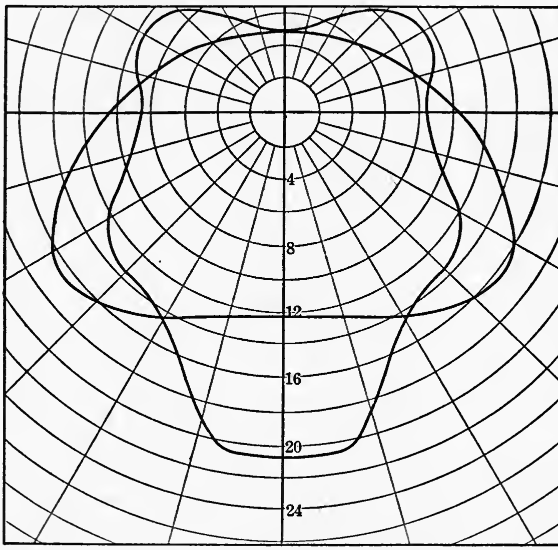


Fig. 96. — Light distribution from prismatic globes.

globes of the same size but with differently designed external prisms.

The form of the curve of distribution obtained from reflectors is dependent upon the original light distribution of the enclosed lamp, the extent of the cone of light intercepted by the reflector, the shape of the reflector or, if prismatic, the design of its prisms, and the position of the lamp. Three general types of light distribution are obtained from reflector units, *uniform* when the light in all directions in the lower hemisphere is practically equal, *distributed* when light is spread outward beneath the lamp and *concentrated* when the light is strongly intensified in a downward

direction. It may be pointed out again that the area enclosed by a distribution curve is entirely without significance and that the downward intensity may be greatly increased at little expense to the intensity near the horizontal.

Diffusing reflectors such as porcelain, enameled metal and opal glass govern the resulting light distribution largely by their contour. Conical reflectors of these materials of rather deep form and of less than 90 deg. angular opening give a strong

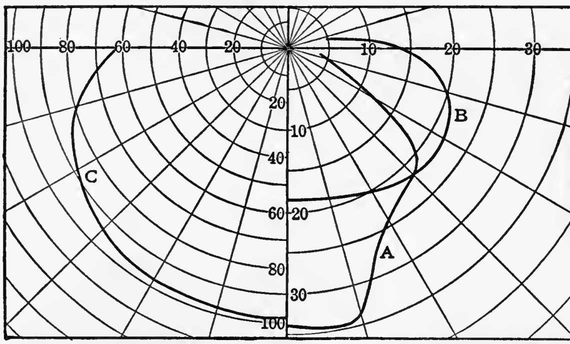
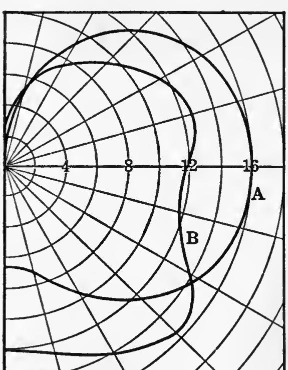


Fig. 97. — Distribution of light from diffusing cone reflectors.

downward concentration. Curve A of Fig. 97 shows the distribution of the familiar green-flashed glass cone reflector. Flat cone reflectors of diffusing surface give a wide distribution when applied to vertical lamps, as in curve B of Fig. 97. Very flat cones placed above horizontal lamps give a uniform lower hemispherical distribution, illustrated by curve C of Fig. 97. Bell-shaped shades of ground glass or opal glass improve the downward intensities and give excellent diffusion at the sides if deep enough to cover the lamp. Fig. 98 shows the form of light distribution given by one of the commoner types.



A - Bare 16 C.P. Lamp.
B - Same with Bell Shade.

Fig. 98. — Light distribution from bell-shaped ground-glass shade with 16 c.p. incandescent lamp.

Mirrored reflectors are very efficient but often lack permanence and are greatly affected by dirt and dust. Their reflection is apt to be

streaky and cause considerable glare unless the surface is corrugated. Polished metal reflectors are less efficient than mirrors and can generally be much improved by coating the reflecting surface with aluminum paint, which gives a permanent and highly reflecting surface.

A great variety of prismatic reflectors has been placed upon the market and they have had a wide use. The distribution of light may be given almost any desired form by the design of the prisms and the contour of the surface. The light transmitted is affected by dirt and dust, but the reflecting power is little influenced thereby unless the dirt accumulates on the lower surface of the glass. In other types of reflectors the position of the lamp in the reflector matters little. In prismatic types the lamp must be carefully set at the focus point of the prisms if the desired distribution is to be secured. This setting is obtained by the use of special shade holders. Typical prismatic reflectors are shown

FIG. 99. Extensive prismatic reflector.

FIG. 100. Focusing prismatic reflector.

FIG. 101. Intensive prismatic reflector.

in Figs. 99, 100 and 101, and their distribution curves in Fig. 102.

Special reflectors are designed to give asymmetric distribution such as is often desired in lighting desks, machinery, show-

windows, works of art, etc. Such reflectors generally give a strongly intensified light in one general direction other than directly downward.

For indirect lighting by small units the lamp is suspended in a metallic bowl whose inner surface is a corrugated mirror designed

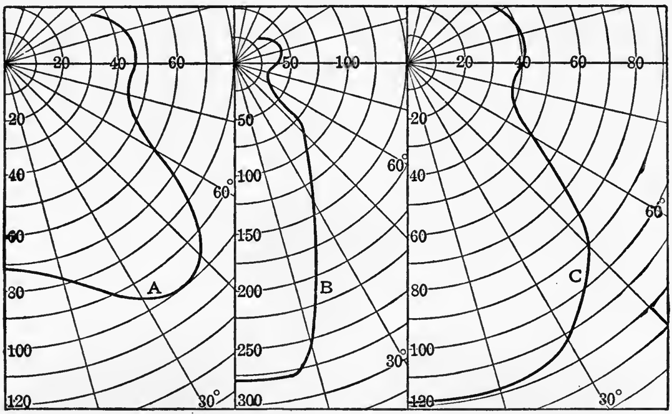


FIG. 102. Light distribution of prismatic reflectors.

A. Extensive, with 100-watt tungsten lamp.
B. Focusing, with 100-watt tungsten lamp.
C. Intensive, with 100-watt tungsten lamp.

to project the light upon the ceiling whence it is distributed about the room. By this means a perfectly diffused and shadowless illumination may be produced.

No uniform method of rating the efficiency of reflecting devices is in vogue. Comparisons may be based upon the ratio of the mean lower hemispherical intensity of the combined lamp and reflector to that of the lamp alone. Laboratory tests made under ideal conditions may differ largely from the performance of the device under actual service conditions due to voltage variations and to the effect of dirt and dust — a fact for which due allowance must always be made in estimates based upon published curves.

Arc lamp reflectors are generally made of enameled metal. In alternating-current carbon arcs a reflector is practically a necessity if the light is to be effectively utilized. In many types of lamp the reflector is a flat white disk surrounding the gas cap, the diameter being small enough to permit its presence

within the outer globe. In other types the reflector is an external flat cone of metal enameled on the lower side.

A special arc lamp reflector known as the concentric light balancing diffuser is employed to secure the effect of semi-indirect illumination in interiors. The best results are obtained from the direct-current carbon arc with the positive electrode beneath. The inner globe is of clear glass and the outer is an inverted bell shade of opal glass which reflects upward a large portion of the light falling upon it. Surmounting the arc is a broad diffusing reflector corrugated with concentric rings and

Fig. 103. — Arc lamp with concentric diffuser.

coated with a special enamel of high reflecting power. The concentric corrugations reduce the effect of the travel of the arc by reflecting the beams in both directions. The enamel surface has a selective absorbing power for the excess violet of the arc spectrum and renders the color of the light better balanced. The light so obtained is white, soft, steadier than that ordinarily obtained from the arc and well distributed for wide illumination. When employed for store lighting the concentric diffuser is incorporated into the ceiling as part of the decorative scheme.

Fixtures.—The fairly endless variety of lighting fixtures and the equally numerous conditions to which individual types are best adapted preclude more than a few general statements of

principles within the present work. Fixtures are to be regarded as both engineering and artistic structures. From the former viewpoint the chief considerations are that the fixture shall support the lamps and their accessories securely and without interference with the most favorable distribution of the light. The materials employed should be chosen for their durability and strength as well as for their artistic possibilities. The structural forms should provide ample rigidity of suspension without excess weight. Flimsy construction and insecure attachment are to be avoided in any case. Fixtures of excessive weight create architectural complications and may endanger the safety of the occupants of rooms.

The wiring of electric fixtures should insure good contact and permanent insulation. Gas fixtures should be free from leaks and dirt. The construction should provide for the convenient renewal and cleaning of the lamps and shades. When simple stock models are extensively used the cost of installation and of maintenance may often be lowered by using fixtures in which the construction is simple and all parts interchangeable. The presence of any metal parts below the lamps results in shadows and ineffective light distribution.

Art glass domes and shades are very inefficient reflectors. Reasonable efficiency may be secured with them by backing the enclosed lamps with efficient reflectors which transmit enough light to give the art glass above a pleasing appearance.

It is quite impossible to formulate a set of definite standards and rules for the judgment of lighting fixtures as artistic structures. The creation of artistic designs belongs to the province of the architect and artist, but the problem of selection often falls upon the engineer. A few simple principles may be stated which are of general application.

Adaptation.—Fixtures are primarily utilitarian in function and secondarily artistic. They are intended to support lamps and fittings and to connect them to the source of supply. Art should be inwrought into the provision for these purely mechanical requirements rather than superficially applied. Superfluous parts whose presence in no way suggests a contribution to the purposes of the fixture offend the artistic sense and are to be avoided.

Proportion requires that the dimensions of the different parts

be those most in harmony with the functions suggested by their position and appearance. There is a manifest incongruity in the use of enormous weights of metal or of hollow structures giving the appearance of great weight to support illuminating devices which weigh but a few pounds. Equal incongruity exists when lamps and shades are supported by tenuous arms bent and twisted into curves which augment their appearance of fragility. Proportion should exist between the fixture and the surrounding architecture as well as between its individual parts.

Harmony in decoration.—Lighting fixtures should not be conspicuous in themselves but should rather be contributory to the general scheme of decoration. Fixtures employed as a part of classical, colonial, ecclesiastical, mission or any other general architectural scheme should in their general structure and decorative detail maintain the closest harmony with their surroundings. Attention should be given to the illuminants themselves as artistic *motifs* without violation of their natural appearance and properties. The torch and the candle now have a recognized artistic value as elements of decoration. The incandescent electric and gas lamps deserve the study of artists to elevate them to a corresponding rank without recourse to imitation or the sacrifice of their natural qualities.

Probably no single principle better sets forth the fundamental requirements than that "artistic success results from the perfect blending of utility and beauty without the subordination of either."

CHAPTER XIII.

THE CALCULATION AND REPRESENTATION OF ILLUMINATION.

THE present chapter deals with the methods of practical calculation and of plotting data and results applicable to illumination problems. The economic and engineering principles of design are considered in succeeding chapters.

Calculation of illumination at points. — With the mean vertical distribution curve of an illuminant at hand the direct illumination at any point P may be computed by the following equations, in which E_n denotes the illumination normal to the beam, E_h the horizontal illumination and E_v the vertical illumination at P, I_θ the intensity of the beam falling upon P, l the length of this beam, l_v the vertical height of the illuminant and l_h the horizontal distance from P to a point directly below the lamp.

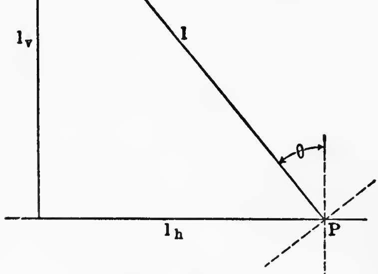


FIG. 104.

$$E_n = \frac{I_\theta}{l^2} = \frac{I_\theta}{l_v^2 + l_h^2},$$

$$E_h = \frac{I_\theta \operatorname{Cos} \theta}{l^2} = \frac{I_\theta \operatorname{Cos}^3 \theta}{l_v^2},$$

$$E_v = \frac{I_\theta \operatorname{Cos} (90 - \theta)}{l^2} = \frac{I_\theta \operatorname{Sin}^3 \theta}{l_h^2}.$$

A table of values of $\operatorname{Cos}^3\theta$ is of value in the application of these formulas. Such a table is given in the appendix (Table XXI). There is also given a table of still greater utility in which are recorded the values of θ, $\operatorname{Cos}^3 \theta/l_v^2$ and $\operatorname{Sin}^3 \theta/l_h^2$ corresponding to given values of l_v and l_h. Sample data from the latter table are reproduced below for purposes of illustration. The value of θ for given

values of l_v and l_h is obtained from table. I_θ is then ascertained from the polar curve and the horizontal illumination at P computed by multiplying I_θ by the constant K_1 given in the table. Vertical illumination at P equals I_θ times K_2.

TABLE XVI. (See Table XXII.)

l_h	l_v = 6 ft.			l_v = 7 ft.			l_v = 8 ft.			l_v = 9 ft.		
	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2
0′	0°	.0278	.0000	0°	.0204	.0000	0°	.0156	.0000	0°	.0127	.0000
1′	9° 30′	.0266	.0045	8° 10′	.0198	.0028	7° 10′	.0152	.0019	6° 20′	.0122	.0014
2′	18° 30′	.0237	.0079	16°	.0180	.0052	14°	.0143	.0036	12° 30′	.0115	.0025
3′	26° 30′	.0200	.0100	23° 10′	.0158	.0068	20° 30′	.0129	.0048	18° 30′	.0106	.0035
4′	33° 40′	.0160	.0106	29° 50′	.0133	.0071	26° 30′	.0112	.0056	24°	.0095	.0042
5′	39° 50′	.0125	.0104	35° 30′	.0110	.0078	32°	.0094	.0059	29° 10′	.0082	.0046
6′	45° 0′	.0099	.0099	40° 40′	.0089	.0076	36° 50′	.0080	.0060	33° 40′	.0071	.0047
7′	49° 20′	.0077	.0090	45°	.0073	.0073	41° 10′	.0067	.0059	37° 50′	.0061	.0047

The utility of the above table and the larger one of which it is a part may be illustrated by an example. Let it be supposed that it is desired to find the horizontal illumination at a point in a plane 7 feet below the illuminant and at a distance of 6 feet from the point directly below the lamp. From the table the angle of the beam with the vertical is found to be 40 deg. 40 min. Suppose the intensity of the illuminant at this angle is shown to be 73.5 candle-power. The horizontal illumination is

$$E_h = I_\theta K_1 = 73.5 \times 0.0089 = 0.654 \text{ foot-candle.}$$

The vertical illumination at the same point would be

$$E_v = I_\theta K_2 = 73.5 \times 0.0076 = 0.566 \text{ foot-candle.}$$

When several illuminants act upon a given point the illumination derived from each is computed and the resultant found by summation.

When the same polar curve is employed in many calculations of horizontal illumination time and effort may be saved by deriving therefrom illumination curves corresponding to the values of l_v most commonly used. Curves of this nature are shown on the typical data sheet of Fig. 106.

The illumination of planes may be represented from the results obtained at different points by illumination profiles and illumination contours. Profiles show the illumination along

representative lines drawn across the plane. Contours are continuous lines drawn on a map of the plane through points of equal illumination. Fig. 105 shows both methods of representation for a room lighted by four illuminants identical in size and light distribution.

Calculation of the mean illumination of planes.—The mean illumination of planes may be approximately determined by averaging the illumination of a large number of representative points. This method involves laborious computations and is far less direct than methods in which the total light flux falling on the plane is approximately determined and is divided by the area of the plane to secure the mean illumination. To apply this process with precision involves the determination of the solid angle subtended at each illuminant by the plane of reference and of the mean luminous intensity within each of these solid angles. The value of the results sought does not warrant the application of such complex mathematical processes and approximate methods are employed in their stead.

The following method of approximation has been found to yield results of fair accuracy when applied to planes of fairly regular outline when the length is not greater than twice the breadth. Assume that the plane has been replaced by a circle of equal area with the illuminants concentrated above its center at their average height of suspension. Let l_r be the radius of this "equivalent circle" and l_v the height of the concentrated illuminants. The cone of "effective flux" is that defined by the angle with the vertical

$$\theta = \mathrm{Tan}^{-1} \frac{l_r}{l_v} \cdot$$

The flux ϕ_θ emitted beneath this angle by each of the illuminants is next determined by the Rousseau diagram, the Kennelly diagram, the fluxolite diagram or by any other of the processes described in Chapter V. The approximate mean illumination of the plane is given by the expression

$$E = \frac{\Sigma \phi_\theta}{A} \cdot$$

The application of this method is facilitated by the use of a table

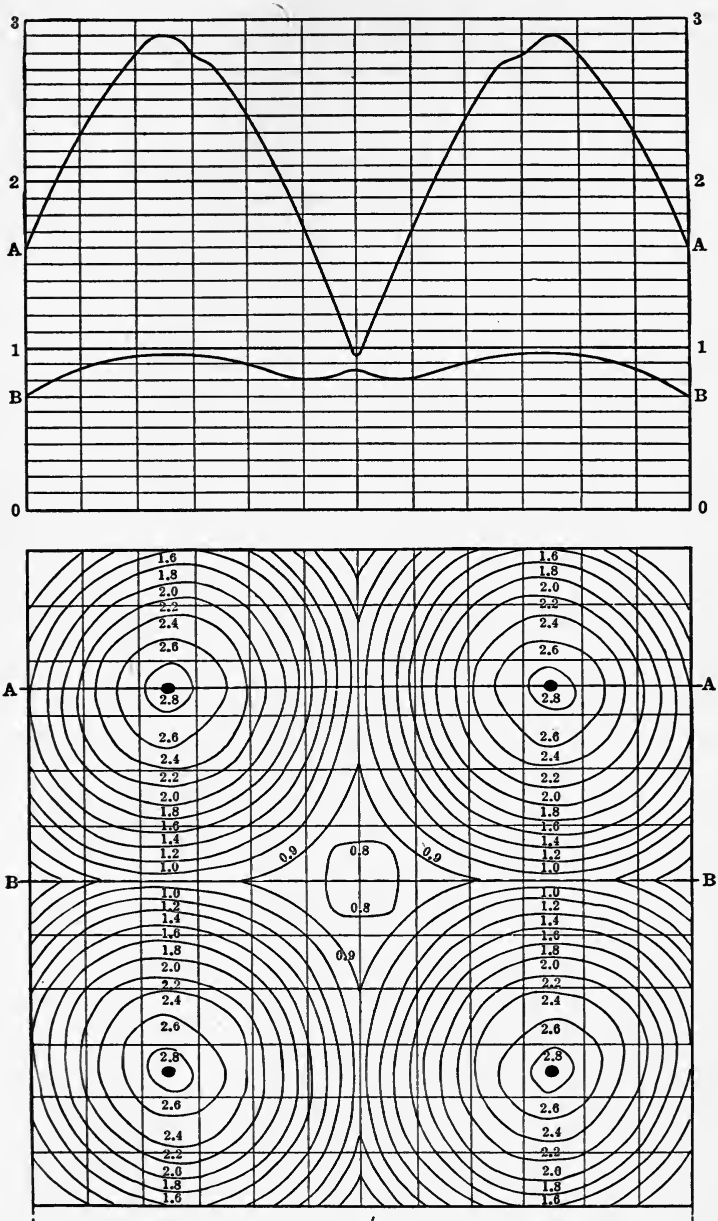


Fig. 105. — Illumination profiles and contours.

in which are recorded the values of θ corresponding to different areas and heights of suspension. Such a table is given in the appendix. When this method is to be applied frequently to a given type of illuminant time and effort may be saved by computing and tabulating the lumens per watt or per cubic foot of gas emitted beneath certain angles. Intermediate values may then be approximated by interpolation. For illustration see the typical data sheet of Fig. 106.

The determination of the number of illuminants of a given type required to illuminate a horizontal plane to a given intensity may be accomplished by a reversal of the above process of computing mean illumination. A suitable height of suspension above the reference plane is assumed and the limiting angle θ of the cone of effective flux found by reference to Table XXIV of the appendix. The flux ϕ_θ given by the illuminant within this cone is next determined and the number of illuminants of this type required computed as follows:

$$N = \frac{EA}{\phi_\theta},$$

N being the number required, E the desired illumination in foot-candles and A the area of the plane.

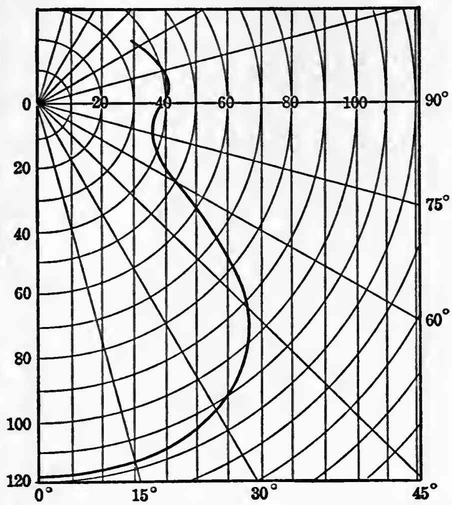
The above method is equally applicable to the determination of the watts of electric energy or the cubic feet of gas per hour required for the illumination of a given plane if the lumens per watt or the lumens per cubic foot per hour within the effective cone are substituted for the value of ϕ_θ in the above expression.

An abridgment of the flux of light method of determining the watts, the number of cubic feet of gas per hour or the number of illuminants of a given type to obtain a certain average illumination has been suggested by Messrs. Cravath and Lansingh.[1] A careful examination of the available data relating to the performance of illumination systems led to the conclusion that an average value of watts expended in illuminants per lumen of flux on the reference plane could be assigned to each type of unit and that preliminary estimates could be made by use of this value. It will be seen that this is equivalent to assuming a certain cone of effective flux to represent a fair average for

[1] Trans. Ill. Eng. Soc., VIII., p. 518.

LAMP - Tungsten
100 Watts
Bowl Frosted.

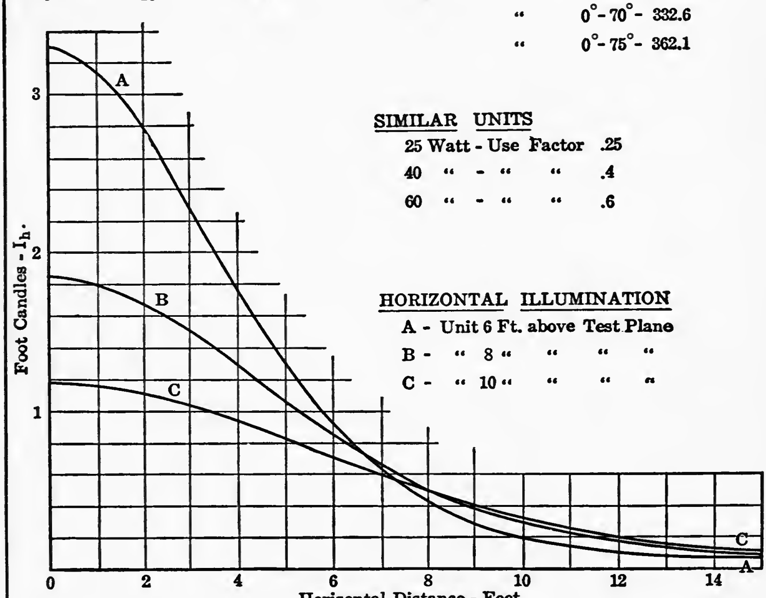
REFLECTOR - Holophane Intensive.
✚ 106180, I9.



UNIT

M.L.H.C.P.	- 66
M.L.H. Lumens	- 414
Watts per M.L.H.C.P.	- 1.5
M.L.H. Lumens per Watt	- 4.14
Lumens,	0°- 60°- 291
Lumens per Watt,	0°- 60°- 2.91

Lumens,	0°- 15°-	24.5
"	0°- 30°-	98.5
"	0°- 35°-	131.0
"	0°- 40°-	165.5
"	0°- 45°-	201.2
"	0°- 50°-	235.3
"	0°- 55°-	265.4
"	0°- 60°-	291.0
"	0°- 65°-	312.9
"	0°- 70°-	332.6
"	0°- 75°-	362.1



SIMILAR UNITS

25 Watt	- Use	Factor	.25
40 "	- "	"	.4
60 "	- "	"	.6

HORIZONTAL ILLUMINATION

A - Unit 6 Ft. above Test Plane
B - " 8 " " " "
C - " 10 " " " "

FIG. 106. — Typical data sheet.

general illumination, the value of lumens per watt for each type of unit being that given within this cone. The values suggested by the originators of this method are given in the next chapter under the head of preliminary estimates.

The **net efficiency** of a system of illumination is determined by dividing the lumens of flux falling upon the reference plane by the total flux emitted by the illuminants. Net efficiency is therefore equivalent to efficiency of light utilization.

Gross efficacy of illumination (commonly termed efficiency) denotes the ratio of total light-flux received by a plane to the watts of electric energy or the cubic feet of gas per hour expended in its production. The result may be expressed as *lumens per watt, lumens per cubic foot per hour,* or as *foot-candles per watt per square foot* as the case may require, the significance and value of the first and the last of these terms being identical.

The secondary or indirect component of illumination is that produced by the light reflected by the walls, ceiling and contents of the room. Some account should be taken of this component, though experience shows that it cannot be predetermined with accuracy. An ideal case may first be considered in which the walls, floor and ceiling have a uniform coefficient of diffuse reflection r and no obstructions are present within the room. The flux of light ϕ emitted within this room falls upon these reflecting surfaces and undergoes successive reflections yielding respectively ϕr, ϕr^2, ϕr^3, etc. As a result of this infinite series of successive reflections there is present in the room and available for illumination the total flux

$$\Sigma\phi = \phi(1 + r + r^2 + r^3 + \ldots r^n).$$

Since r is less than unity the above infinite series may be reduced to

$$\Sigma\phi = \frac{\phi}{1 - r}.$$

For example, in a room with walls, ceiling and floor completely coated with white paper having a value of r equal to 0.70 and in which light is distributed from an illuminant uniformly in all directions the actual flux across any plane would be 3.33 times that due to the direct beams.

It is self-evident that no such ideal conditions prevail in practice. The floor and its coverings, the furnishings of the room

and the extreme lower portions of the walls have little effect in reflecting light downward onto a horizontal reference plane and generally contribute little to the general illumination of other surfaces. Allowance must also be made for dark hangings, open spaces and obstructions. Furthermore, when reflectors are employed the greater part of the light is thrown downward toward the least effective secondary reflecting surfaces. The true value of the secondary component of illumination seldom exceeds one half the amount indicated by the above formula. For any particular case it may be found experimentally by measuring the illumination, first with the walls, ceiling and floor entirely covered with dead black material and with all contents removed from the room, and subsequently with all conditions as in actual service. Caution should be observed in applying the data of such tests to other cases. They are generally inapplicable unless the type of illuminant, the height of its suspension, the color and texture of the walls and ceiling and all other general conditions are quite similar. In none of the calculations of illuminating engineering are experience and trained judgment more requisite than in the determination or estimation of the indirect component of illumination.

Theoretical conditions of uniform illumination.[1]—The familiar equation for the calculation of horizontal illumination,

$$E_h = \frac{I_\theta \operatorname{Cos}^3 \theta}{l_v^2},$$

may readily be employed to determine the form of light distribution required for the uniform illumination of limited areas. For a single unit the resulting distribution curve for uniform illumination is shown in Fig. 107. Obviously the area which can receive uniform illumination from a single unit is limited because of the increase of the required intensity with the departure of the beam from the vertical. Large clusters or chandeliers for interior illumination might advantageously be

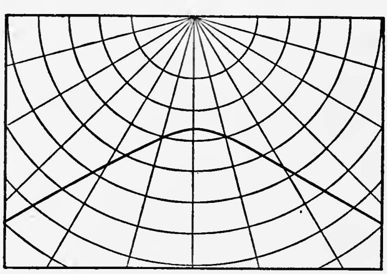


Fig. 107. — Form of light distribution required for uniform illumination from a single illuminant.

[1] Elec. World., Dec. 21, 1907, Mar. 21, 1908, June 27, 1908.

designed to meet the required conditions through a zone of perhaps 50 deg.

In the general case more than a single unit is required and the general illumination is obtained from the overlapping of the areas above which the individual units are effective. The simplest case of this nature is that in which the illumination from a given lamp is a maximum directly beneath that lamp and diminishes gradually to zero directly beneath the next adjacent lamp. If the lamps are placed at the corners of squares their effective areas will overlap as shown in Fig. 108. Fig. 109 shows the type of distribution curve and resulting illumination curves most effective with this arrangement for a particular ratio of height of suspension l_v to lamp spacing l. When such illuminants are suspended at the corners of squares at a height l_v above the plane illuminated and with the spacing l the illumination secured is uniform and is equal to that produced by each unit alone at the point directly beneath; or,

$$E = \frac{I_0}{l_v^2}.$$

The limiting angle of the effective zone of each unit is

$$\alpha = \mathrm{Tan}^{-1}\frac{l}{l_v};$$

whence

$$l = l_v \tan\alpha = \sqrt{\frac{I_0}{E}}\tan\alpha.$$

The number of units required for the entire area is evidently

$$N = \frac{A}{l^2} = \frac{AE}{I_0 \tan^2\alpha}.$$

The above method of producing uniform illumination assumes a definite ratio of the height of suspension l_v to the spacing l which we may denote by K. If the lamps are hung lower with the same spacing the reference plane will receive the same total flux of light, but the uniformity will be lost, the intensity being greatest beneath each lamp. Weinbeer has shown that increasing the constant K by raising the lamps does not affect either the uniformity or value of the illumination if the total area is large compared with that above which each lamp is effective.

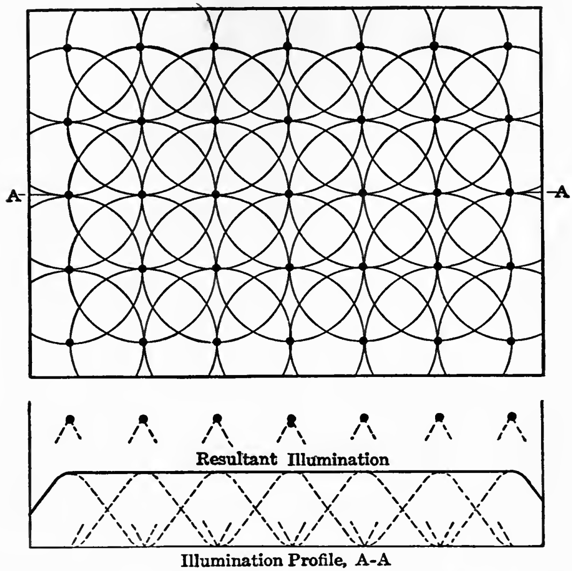


FIG. 108. — Uniform illumination by overlapping effective areas.

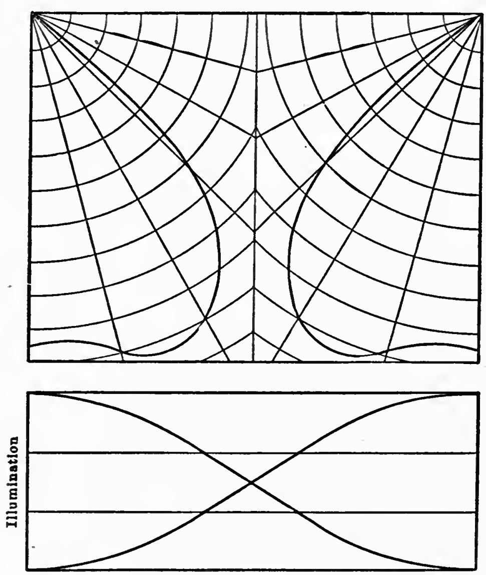


FIG. 109. — Distribution and illumination curves for uniform illumination by overlapping effective areas.

If the spacing of the lamps is diminished without changing their height the uniformity remains unimpaired but the actual value of the illumination increases in direct proportion to the total number of units. In other words, there exists a certain ratio of height of suspension to spacing for the ideal illuminants of Fig. 109 below which uniform illumination cannot be secured but above which uniform illumination is always secured.

All the above conclusions are strictly theoretical and hold only for the ideal distribution curves of Fig. 109. Many practical units approximately meet these conditions for values of α between 45 and 60 deg. Such illuminants are well adapted to produce uniform illumination of large areas if so employed that the ratio of the height of suspension to the spacing does not fall below the critical value tan α. The number of such units required to produce the desired uniform illumination may be approximated from the formula

$$N = \frac{AE}{\phi_\alpha},$$

ϕ_α being the flux per unit beneath the limiting angle of useful flux α. This method is seen by a little thought to be identical in significance with the abridged light flux method previously described. Data for the practical application of this method of estimating the installation required will be given in the next chapter.

CHAPTER XIV.

ENGINEERING AND ECONOMIC PRINCIPLES IN INTERIOR ILLUMINATION.

A COMPLETE discussion of this subject might well occupy an entire volume. The limitations of a single chapter permit the consideration of general principles only with no attempt to formulate rules for individual problems.

Relation to architecture.—Clear distinction must be made between cases of illumination in which the chief considerations are commercial and those in which they are artistic. The former belong to the jurisdiction of the engineer and the latter to the architect. In both cases the primary need of "good light to see by" must be met, but the methods of treatment may differ widely. Engineering problems should be treated in full harmony with the general architecture rather than in spite of it. The laws of good taste, adaptation, proportion and decorative harmony should be inwrought with engineering methods, however utilitarian the results desired.

The reference plane in interior illumination should be chosen to represent the positions in which the light is most directly useful. In the majority of cases a horizontal plane from 30 to 48 inches above the floor, coinciding in level with the tops of tables, desks, counters, etc., may most appropriately be selected, but there are manifestly many cases in art galleries, display rooms, libraries, theater stages, etc., where vertical planes are of greater significance. The illumination of rooms is designed and measured in terms of that of the reference planes. The net efficiency of illumination denotes the percentage of the total flux of light generated which falls upon the reference plane, and its gross efficiency is measured by the lumens on the reference plane per watt or per cubic foot of gas expended in the illuminants. On the other hand, the adequacy and efficiency of the reference plane illumination are not infallible indices for the entire room, and a general account must be taken of second-

ary planes, which for the sake of simplicity are left out of the account in calculations and tests.

Systems of illumination may be classified broadly as *direct* and *indirect*. In the former the greater part of the light falls upon the reference plane as the direct rays of the illuminants. In the latter the lamps are concealed from view and the illumination is accomplished entirely by reflected light derived from the ceiling and the upper part of the walls. In cases of direct illumination there is always an indirect component whose magnitude depends upon the light directed toward the ceiling and walls and upon their reflecting power. In some cases this secondary component is of considerable importance. Direct illumination may be either general or concentrated and in many installations both are provided for.

The relative merits of direct and indirect illumination are much in dispute. Indirect illumination is valuable for the elimination of all shadows, the great uniformity of light and the low intrinsic brilliancy which characterize it. Experiments indicate that the eye requires a higher degree of illumination by indirect methods than by direct for the same satisfaction in working. Especially is this true where the lower portions of the walls and the surrounding objects in the room which the eye does not view directly are of high luminosity, for the eye then lacks the restful assistance of contrasted brightness when glancing away from its work. Indirect illumination renders the ceiling the brightest surface in the room and vision is improved by shading the eyes as when working beneath a bright overhead sky. In drafting-rooms and offices where an entire elimination of shadows is desired indirect lighting is of great and recognized value. In other cases it may be regarded as something of a luxury as it is an essentially inefficient mode of light utilization. Where color contrasts are lacking, as in foundries, seeing must be done largely by the aid of shadows and direct lighting is indispensable.

Illumination requirements.—Attention should be recalled at this point to the principles developed in Chapter IV and summarized at its conclusion. The prime requisite is that of ample illumination, after which follow low brilliancy, proper light direction, uniformity, steadiness and color balance. The first criterion to be met requires that all surfaces which receive the

close and continuous attention of the eye shall have a mean luminosity of not less than one lumen per square foot and more in special cases. We may class all cases requiring an illumination of the reference plane of 4 foot-candles or more as bright illumination. In this class are found such cases as drafting-rooms, theater stages, engraving shops, stores displaying dark merchandise, and machinery requiring delicate adjustment. From 1 to 4 foot-candles suffice for medium illumination such as is generally required for ordinary stores, office desks, reading tables, libraries, churches, auditoriums, school rooms, residences, and public corridors. Low illumination of less than 1 foot-candle suffices in warerooms and shops where adequate local illumination is provided wherever required. The dividing lines between these classes are somewhat arbitrarily chosen for convenience in estimating installations.

Preliminary estimates for direct lighting should be made if possible before the location and selection of illuminants have been decided upon. Such estimates serve as guides in the comparison of illuminants and in the problem of their most effective distribution. Estimates may be made by purely empirical methods, but those of greatest value have a rational scientific foundation. The following empirical estimates assume the rooms to be of medium height, the walls and ceiling to be of fair reflecting power and the light distribution of the illuminants to be of a favorable type. For conditions more or less favorable than the average the estimates may be modified accordingly.

Estimates based upon cubic feet per mean spherical candle-power.

Bright Illumination	1 m. s. c. p. to 30 cu. ft. or less
Medium Illumination	1 m. s. c. p. to 30 to 60 cu. ft.
Low Illumination	1 m. s. c. p. to 60 to 100 cu. ft.

Estimates based upon square feet of floor space per mean spherical candle-power.

Bright Illumination	1 m. s. c. p. to 2.0 sq. ft. or less
Medium Illumination	1 m. s. c. p. to 2 to 4 sq. ft.
Low Illumination	1 m. s. c. p. to 4 to 6 sq. ft.

A third method of estimating rests upon a more scientific basis than the two above outlined, viz., the application to the

problem of the operating results of other installations of a similar nature. Data of this nature are not abundant and those available often fail to meet the local conditions, requiring experienced judgment in taking account of the variables. The estimates given in Table XVII are compiled from the data of actual tests but should be used with the realization of their dependence upon such conditions as the nature of the reflecting and diffusing agencies, the condition of the walls and ceilings, the presence of obstructions, the height of suspension, etc.

A fourth method of estimating is developed in the preceding chapter and consists essentially in ascertaining the limiting angle of the cone of useful flux for the area and the assumed height of suspension, the flux given by each of the illuminants considered within this cone and, from these data, the number of illuminants required to give the aggregate flux required on the reference plane. This process may be abridged by assuming that the watts required per effective lumen or the cubic feet of gas per effective lumen have the values given in Table XVII, so that the third method is in reality a simplification of what is here designated as the fourth method.

After the preliminary estimate of the required installation is complete a tentative distribution of the illuminants about the room may be assumed and the illumination at some of the most important points in the reference plane checked up by actual calculation.

With the preliminary estimate of the installation required completed, there remain the problems of the selection of the illuminants and their accessories and of their location to secure the best effect. Obviously no definite rules can be laid down to govern these problems. A few of the more pertinent considerations may be pointed out.

The choice of illuminants includes the selection of such accessories as shades, reflectors, etc., as few lamps possess the natural light distribution most favorable to downward illumination, and the resulting unit should be considered as a whole.

The economic problem involved in this selection is simplest stated as that of producing the desired illumination at the lowest cost. This cost may be analyzed into two general items,

TABLE XVII. — ESTIMATES OF WATTS REQUIRED PER LUMEN ON THE REFERENCE PLANE.[1]

INCANDESCENT LAMPS.	
Tungsten lamps rated at 1.25 watts per horizontal candle-power; clear prismatic reflectors, either bowl or concentrating; large room; light ceiling; dark walls; lamps pendant; height 8 to 15 feet	0.25
Same with very light walls	0.20
Tungsten lamps rated at 1.25 watts per horizontal candle-power; prismatic bowl reflectors enameled; large room; light ceilings; dark walls; lamps pendant; height 8 to 15 feet	0.29
Same with very light walls	0.23
Gem lamps rated at 2.5 watts per horizontal candle-power; clear prismatic reflectors either concentrating or bowl; large room; light ceiling; dark walls; lamps pendant; height 8 to 15 feet	0.55
Same with very light walls	0.45
Carbon filament lamps rated at 3.1 watts per horizontal candle-power; clear prismatic reflectors either bowl or concentrating; light ceiling; dark walls; large room; lamps pendant; height 8 to 15 feet	0.65
Same with very light walls	0.55
Bare carbon filament lamps rated at 3.1 watts per horizontal candle-power; no reflectors; large room; very light ceiling and walls; height 10 to 14 feet	0.75 to 1.5
Same; small room; medium walls	1.25 to 2.0
Carbon filament lamps rated at 3.1 watts per horizontal candle-power; opal dome or opal cone reflectors; light ceiling; dark walls; large room; lamps pendant; height 8 to 15 feet	0.70
Same with light walls	0.60
Westinghouse-Nernst lamps, alabaster balls, no reflectors; large room; light ceiling; medium walls	0.276
Same; dark walls	0.348
ARC LAMPS.	
5 ampere, enclosed direct current arc on 110 volt circuit: clear inner, opal outer globe; no reflector; large room; height of lamps 9 to 14 feet	0.50
Mercury arc, white dihedral reflector; large room; medium walls and ceiling; height of lamps 9 to 14 feet	0.18

GAS LAMPS.[2]

The following constants indicate the cubic feet per hour required for each effective lumen with ordinary gas and good mantles.

Type of Burner.	Light room.	Dark room.
Open flame	0.045	0.077
Upright mantle burner, bare	0.013	0.31
Upright mantle burner with globe	0.020	0.037
Upright mantle burner with fluted flat cone	0.012	0.020
Upright burner with opal dome and bobesche	0.013	0.017
Inverted burner, bare	0.008	0.012
Inverted burner, ground-glass shade	0.009	0.013
Inverted burner, prismatic reflector	0.0064	0.0071
Cluster, 4-burner upright	0.0127	0.0169
Cluster, 3-burner inverted	0.0800	0.0122

[1] Trans. Ill. Eng. Soc., Vol. III, p. 518.

[2] Trans. Ill. Eng. Soc., Vol. IV.

fixed charges and variable or operating charges. Stated in the form of an equation the result desired is:

$$\frac{\text{Annual fixed charges} + \text{Annual operating charges}}{\text{Annual lumen-hours secured}} = \text{Minimum.}$$

The fixed charges consist of interest and depreciation and are determined by the cost of purchase and installation of the permanent elements of the system and by the period of their useful life. In estimating depreciation charges the probable advance of the art must be taken into account as well as the physical life of the apparatus. Antiquation is often a greater cause of depreciation in lighting systems than actual decay. Whenever possible the design of the system should anticipate the trend of progress so that readjustment may be made from time to time without greatly adding to the permanent investment. Depreciation charges should be so proportioned that their accrual during the useful life of the installation shall entirely cover the first cost.

The variable charges represent the combined cost of energy supply, renewal of parts, attention and repairs incidental to the normal operation of the system. Under the head of attention special note may be made of the item of cleanliness. Many units are seriously affected by the gradual accumulation of dirt and require frequent cleaning to maintain a satisfactory standard of efficiency. Allowance should be made for this element of expense in estimating maintenance costs. Other considerations being equal such units as possess an inherent tendency to cleanliness are much to be preferred. These items require a careful balancing among themselves to secure the best economy. The use of highly efficient lamps which are expensive of renewal may give the lowest operating costs when the price of electric energy or gas is high. On the other hand inefficient lamps which cost little to renew may give a greater actual economy with cheap energy. These facts are concretely illustrated in Fig. 110 in which are compared the operating and renewal costs of carbon and tungsten lamps of 32 candle-power each. With energy costing less than 1.25c per kilowatt-hour the greater economy is secured with the less efficient carbon lamps, but for higher energy costs, the reverse is true.

The most economical proportioning of fixed and variable

charges is largely determined by the amount of service required of the system. An efficient but expensive installation with a poor load factor may result in an undue proportion of fixed charges. A very cheap and inefficient system with a high load factor leads to an undue proportion of operating costs.

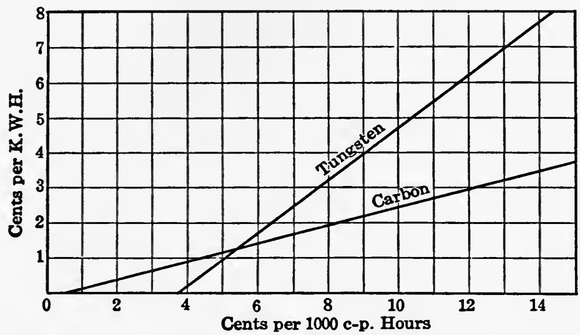


Fig. 110. — Comparative cost of light with carbon and tungsten lamps.

Service requirements require no less careful consideration in the selection of illuminants than the economic problem. Each case constitutes practically an individual problem and calls for the exercise of skilled judgment. A few of the more important considerations to be taken into account may be mentioned — architectural adaptation, decorative value, the character of the service available, flexibility in the size and control of units, ease of installation, mechanical ruggedness, the liability of the theft and breakage of lamps, accessibility for renewal and cleaning, the color value demanded and the general nature of the eye work to be done by the aid of the light. Experience and judgment alone can suggest the precise relation of each of these matters to any case.

The location of units and fixtures which will be most effective must be determined by the conditions of each individual case rather than by general rule. It is fairly axiomatic that the illuminants should be so placed as to illuminate best the objects to be seen without the interference of shadows and without throwing a glare into the eyes of persons working by aid of the light. Uniformity may be regarded as desirable but not indispensable if the illumination does not vary over wide limits and the minimum be ample for effective vision. The many archi-

tectural and decorative considerations which enter into the problem of placing light sources are too numerous to be catalogued here. In no case, however, should other considerations be allowed precedence over the adaptation of the system to the needs of vision as set forth in Chapter IV.

Illumination plans may be conveniently prepared from architect's floor plans by marking upon them the positions of the required outlets. A code of standard symbols by which these outlets may be identified has been prepared by the National Electrical Contractors' Association and its use is recommended. An index number or letter may also be assigned to each outlet which refers to a tabulated schedule of specifications indicating the exact nature of the fittings to be attached to each outlet.

Tests of illumination furnish the engineer with a valuable check upon his designs and estimates and provide data by which the lay-out of future installations may be more intelligently accomplished. The most important data to be secured by such tests are the mean illumination of the reference plane, the net efficiency of light utilization, the gross efficacy in watts expended per lumen on the reference plane and the per cent of deviation of the maximum and minimum illumination from the mean. Close attention must be paid to the regulation of the voltage of the system or its gas pressure to the normal working value. Neglect of this item may render the results of the test valueless, or may lead to erroneous conclusions when different methods of illumination are compared. To arrive at the true mean illumination of the reference plane a large number of observations must be made to avoid the drawing of conclusions from inadequate data. To secure the highest accuracy the entire test plane should be subdivided into small units of area and a test station taken at the center of each. When large test areas may be divided into several smaller areas in which the same arrangement and sizes of lamps are found, as, for example, the bays of large retail stores, a representative bay may be selected and subdivided into elementary areas with a test station at the center of each. If the bay can be considered as made up of two or more sections symmetrically situated with respect to the light sources, the test stations may be confined to one of these symmetrical sections. All the illuminants in the room should be lighted when the test is made. It is recommended that four observations be made

at each test station, the voltage being read at the time of each observation, so that deviations from normal may be properly corrected for. The power consumption of the system at its normal voltage should be accurately determined.

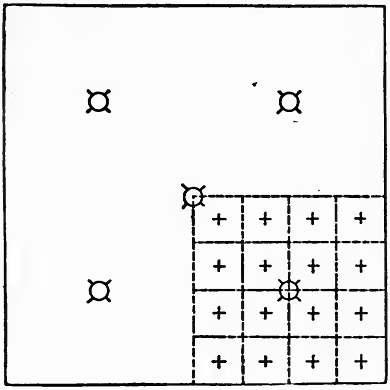


FIG. 111. — Test stations in a bay of a large room.

It is not required in all tests to determine the precise mean illumination of the test plane, and good judgment will dictate the selection of test stations which will yield the information desired. In competitive tests of different systems and in the accumulation of data as a basis of future designs the equal subdivision of a definitely representative section of the test plane should be strictly adhered to.

As in all classes of photometric measurement the use of accurately standardized instruments cannot be too strongly insisted upon in tests of room illumination. The record of the test should include a statement of the nature of the ceiling and walls, and of the character of the contents of the room which may affect the illumination. A sketch should be made indicating the plan of the room, the location of the illuminants, and the location of the test stations with reference numbers for their identification. Careful records should also be made of the height of the illuminants and the height of the test plane above the floor.

CHAPTER XV

EXTERIOR LIGHTING.

Exterior lighting, except that employed for spectacular and advertising purposes, is intended to facilitate night traffic, to raise the standards of public safety and to add decorative effect to city streets. In densely traveled districts street lighting should provide for the actual illumination of all parts of the thoroughfares. Where traffic is infrequent a system of beacon lights to mark the course of the streets and their intersections meets the actual requirements.

The search for standards by which methods of street illumination may be compared reveals an unfortunate disagreement in the methods of measurement. European engineers agree in the measurement of the horizontal illumination one meter above the level of the street. The British standard differs from this in the height of the test plane, which is usually taken at four feet. American engineers are divided in the preferences between the British standard, horizontal measurements at the pavement level, vertical measurements at a height of four feet, and measurements normal to the direction of the beam. Each standard of measurement has its quota of advantages and disadvantages. When the distance between lamps is greater than twice their height the large angle of incidence necessarily renders the horizontal illumination in the middle of the space lower than the normal or vertical value, and correspondingly more difficult of measurement. In fact, there are many American streets of importance whose minimum horizontal illumination defies measurement by any known device. However, the horizontal value is the only one which takes full account of the joint effect of several lamps, especially where they are closely spaced. A certain standard minimum of horizontal illumination insures a much higher standard of actual illumination than the same minimum in a vertical or a normal plane. It is argued that vertical illumination is that which is most useful for vision and

that normal illumination furnishes the best conditions for actual measurement. Normal measurements made at a distance of 250 feet have received the official sanction of the National Electric Light Association[1] as the basis of its standard rating of arc lamps.

Satisfactory standards of street illumination depend upon the extent of the traffic to be served. A standard cannot be defined solely in terms of mean illumination, for a given mean value with strong contrasts between maxima and minima is distinctly inferior to uniform illumination of the same mean value. In practically all existing methods of lighting the illumination is greater nearer the source than at a distance and an adequate minimum standard insures a fair average. In many important European thoroughfares a minimum horizontal standard of 0.1 foot-candle is required. American standards are distinctly inferior and generally inadequate, but show a strong upward trend.

We may group the existing devices for street lighting into three general classes, large units intended for high suspension and relatively long spacing, small units for low suspension and close spacing and decorative clusters of small units. The first class comprises electric arcs of the carbon, flame and metallic oxide types and gas clusters, and finds its distinctive field where streets are relatively free from trees and obstructions. Units of this type are most effective when suspended from 20 to 30 feet above the center of the street, and for particularly brilliant effects they are often used singly or in pairs with ornamental iron standards set at the curb lines with relatively short spacing.

The second class comprises incandescent electric and gas lamps. These are usually mounted on standards or brackets from 7 to 10 feet high upon the curb lines, the spacing on the two sides of the street being staggered to give the greatest uniformity. Units of this class closely spaced are found very effective in shady streets and upon curved driveways. An effective combination of center lighting by large units at the intersections and curb lighting by small units in the middle of the block gives excellent results in long and shady blocks.

The third class is now largely used for the decorative lighting of important city streets. The clusters are supported by massive iron pillars of artistic design set opposite each other at the curb

[1] N. E. L. A., 1908, Vol. I, p. 580.

lines. The lamps are enclosed in large diffusing globes which present a beautiful appearance and, when properly arranged, give an excellently diffused and distributed light. When it is not desired to keep all the lamps burning throughout the night separate switching connections are made with the lamps in the upper globe so that these may be operated alone. Spectacular lighting by arches of incandescent electric lamps spanning the streets at frequent intervals has had considerable vogue. It is not an effective means of utilizing light for illumination.

The distribution of light most favorable for street lighting depends upon the height and spacing of the lamps. The value of large units with long spacing is largely determined by their intensity above 70 deg. with the vertical. A marked maximum of intensity between 75 and 80 deg. with the vertical is desirable. Fig. 69 compares the light distribution of (A) the 6.6-ampere open direct-current carbon arc, (B) the 6.6-ampere enclosed direct-current arc, (C) the 7.5-ampere enclosed alternating-current arc and (D) the 6.6-ampere enclosed alternating-current arc with small reflector. Fig. 78 compares the 4-ampere magnetite arc and the 6.6-ampere magnetite arc. The normal illumination curves of the same units are compared with similar notation, indicating the distinct superiority of the units with strong sidewise distribution. Tests of illuminants in place give lower values than laboratory tests, but tend to show the same relative values. Flame arcs have been little used for street lighting in America, but are employed in considerable numbers in Europe. In Figs. 74 and 75 the distribution curves and the normal illumination curves of the prevailing types of flame arc are compared, the advantage of the vertical arrangement of electrodes being apparent when a widespread illumination is desired.

The height of suspension of arc lamps which give their maximum intensity of light distribution much below the horizontal is an important factor in determining the uniformity of the illumination obtained and its minimum between lamps. Figure 112 shows the relation between the distribution of normal illumination and the height of suspension of a flame arc with inclined electrodes, having a clear outer globe and a prismatic inner globe to intensify the sidewise distribution and diffuse the light. The result is apparently paradoxical as the increase of the

suspension height produces an increase of the illumination at some distance from the lamp, and greatly improves its uniformity.

The most effective height of suspension for carbon arcs is doubtless greater than that commonly employed, which is frequently

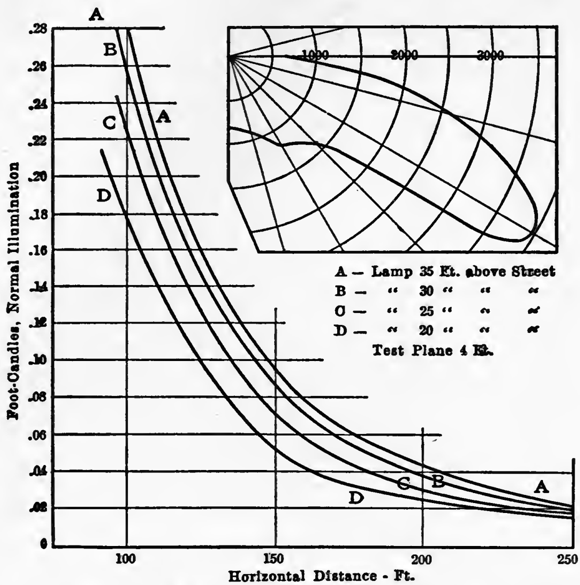


FIG. 112. — Effect of height of suspension on normal illumination from flame arc with inclined electrodes and prismatic inner globe.

determined by the need of accessibility for trimming. Flame arcs evidently require relatively high suspension to render them effective over an extended area. For magnetite arcs a height of 25 feet has been found quite effective in practice.

A standard commercial rating of arc lamps in terms of their actual illuminating value was adopted by the National Electric Association[1] in 1908. The "nominal 2000 candle-power" rating previously employed had no significance in indicating illuminating values, and its indefinite meaning was a source of embarrassment and legal complications. The present ratings are based upon an extensive photometric investigation of lamps in service and are determined by the normal illumination from the lamp at a distance of 250 feet. The rating denotes the ratio of this distance to that at which the same illumination could be

[1] N. E. L. A., 1908, Vol. 1, p. 580.

derived from a 16 candle-power lamp. The values assigned are given in Table XVIII.

TABLE XVIII. — STANDARD COMMERCIAL RATING OF ARC LAMPS.

4.0-amp., d. c. series magnetite arc lamp	5.5
9.6-amp., d. c. series open arc	4.0
6.6-amp., d. c. series enclosed arc	4.0
7.5-amp., a. c. series enclosed arc	4.0
6.6-amp., a. c. series enclosed arc	3.5
6.6-amp., d. c. series open arc	3.5
5.0-amp., d. c. series enclosed arc	3.5
5.5-amp., a. c. series enclosed arc	3.0

Large street lighting units operated by gas are but little employed in America. Excellent installations operated on the high pressure and the self-intensified principles are found in Europe.

Small street lighting units consist of gas mantle burners, naphtha mantle burners, gasoline mantle burners, and both series and multiple incandescent electric lamps. Gas mantle burners rank next in importance to arcs as agencies for street lighting. Careful attention is required to keep the standard of their operation up to a reasonable value. Naphtha and gasoline mantle burners are much in favor where no central source of gas and electric supply exists. Series incandescent electric systems have in the past been but partially successful due to the prevailing low standards of installation, attention and operation. With the advent of the tungsten street series lamp great strides have been made toward standards of efficiency comparable to those of the best arc lighting systems.

The economic value of carefully designed reflectors is illustrated in Fig. 113, which shows distribution curves for an 80 candle-power tungsten series lamp equipped with various forms of reflectors. The prismatic bowl reflector is based upon the unique principle of intensifying the light on the street side of the lamp. The form of its horizontal distribution is indicated in Fig. 114.

The economic problem in street lighting is no less important than the technical problem. It should be approached from the point of view of the actual illuminating results secured rather than that of blind economy in the contract price per lamp year. On the other hand it is not to be recommended that photometric

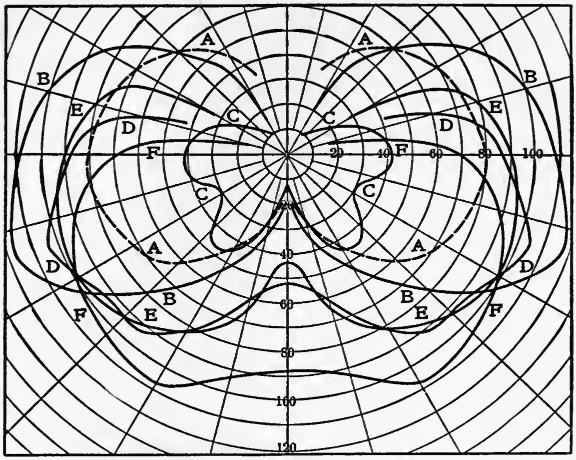


FIG. 113. — Distribution curves of 80 c.p. tungsten series tungsten lamp; (*a*) bare lamp; (*b*) with prismatic reflector — street side $22\frac{1}{2}°$ from curb line; (*c*) with prismatic reflectorhouse side, $22\frac{1}{2}°$ from curb; (*d*) with radially fluted enameled metal reflector, 18″ without guard; (*e*) with 22″ enameled street hood; and (*f*) with 18″ flat tin shade.

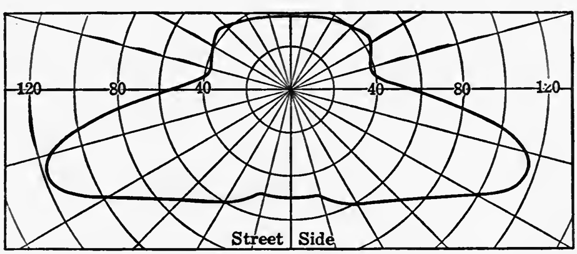


FIG. 114.— Horizontal distribution of prismatic reflector for street lighting.

tests on the streets be made the sole criterion of contracts and rates of payment. The great number of observations required to arrive at average results, the technical difficulties of measurement of low values of illumination and the over-emphasis of personal factors of observation to which the conditions give rise introduce uncertainties incompatible with legal requirements. The actual life of street lighting systems over which the first cost may be distributed as depreciation seldom exceeds ten years. This short life is due more to antiquation than to decay. In most street lighting installations the proportioning of fixed and

variable charges is more readily accomplished than in systems for interior lighting, since the number of hours of actual operation of the system per annum can usually be quite accurately predicted and the operating, renewal and maintenance cost figured accordingly.

Municipal lighting has suffered greatly from being treated as a political bagatelle without due recognition of the great public and commercial value of high grade lighting. Undoubtedly no field of activity affords the illuminating engineer richer opportunity for constructive progress and large public service.

APPENDIX.

Containing tables and charts to facilitate photometric and illumination computations, and the preparation of estimates and plans for illumination installations.

TABLE XX. — CORRECTION FACTORS

To reduce observed flow to standard value multiply

Bar. Pres.	Temperature of Gas.										
	40°	42°	44°	46°	48°	50°	52°	54°	56°	58°	60°
28.0	.979	.974	.970	.965	.960	.956	.951	.946	.942	.937	.932
28.1	.983	.978	.973	.969	.964	.959	.955	.951	.945	.941	.936
28.2	.986	.981	.977	.972	.967	963	.958	.953	.949	.944	.939
28.3	.990	.985	.980	.976	.971	.966	.961	.957	.952	.947	.942
28.4	.993	.988	.984	.979	.974	.970	.965	.960	.955	.951	.946
28.5	.997	.992	.987	.983	.978	.973	.968	.964	.959	.954	.949
28.6	1.001	.995	.991	.986	.981	.977	.972	.967	.962	.958	.953
28.7	1.004	.999	.994	.990	.985	.980	.975	.970	.966	.961	.956
28.8	1.007	1.003	.998	.993	.988	.984	.979	.974	.969	.964	.959
28.9	1.011	1.006	1.001	.997	.992	.987	.982	.977	.973	.968	.963
29.0	1.014	1.010	1.005	1.000	.995	.990	.986	981	.976	.971	.966
29.1	1.018	1.013	1.008	1.004	.999	.994	.989	.984	.979	.975	.969
29.2	1.021	1.017	1.012	1.007	1.002	.997	.992	.988	.982	.978	.973
29.3	1.025	1.020	1.015	1.011	1.006	1.001	.996	.991	.986	.981	.976
29.4	1.028	1.024	1.019	1.014	1.009	1.004	.999	.995	.990	.985	.980
29.5	1.032	1.027	1.022	1.018	1.013	1.008	1.003	.998	.993	.988	.983
29.6	1.036	1.031	1.026	1.021	1.016	1.011	1.006	1.001	.996	.992	.986
29.7	1.039	1.034	1.029	1.025	1.019	1.015	1.010	1.005	1.000	.995	.990
29.8	1.043	1.038	1.033	1.028	1.023	1.018	1.013	1.008	1.003	.998	.993
29.9	1.046	1.041	1.036	1.031	1.026	1.022	1.017	1.012	1.007	1.002	.997
30.0	1.050	1.045	1.040	1.035	1.030	1.025	1.020	1.015	1.010	1.005	1.000
30.1	1.053	1.048	1.043	1.038	1.033	1.029	1.024	1.019	1.014	1.009	1.003
30.2	1.057	1.052	1.047	1.042	1.037	1.032	1.027	1.022	1.017	1.012	1.007
30.3	1.060	1.055	1.050	1.045	1.040	1.036	1.030	1.025	1.020	1.015	1.010
30.4	1.064	1.059	1.054	1.049	1.044	1.039	1.034	1.029	1.024	1.019	1.014
30.5	1.067	1.062	1.057	1.052	1.047	1.042	1.037	1.032	1.027	1.022	1.017
30.6	1.071	1.066	1.061	1.056	1.051	1.046	1.041	1.036	1.031	1.026	1.020
30.7	1.074	1.069	1.064	1.059	1.054	1.049	1.044	1.039	1.034	1.029	1.024
30.8	1.078	1.073	1.068	1.063	1.058	1.053	1.048	1.043	1.037	1.032	1.027

FOR VOLUME AND FLOW OF GAS.

by factor corresponding to conditions.

Bar. Pres.	Temperature of Gas.										
	62°	64°	66°	68°	70°	72°	74°	76°	78°	80°	82°
28.0	.927	.922	.917	.912	.907	.902	.897	.892	.887	.881	.875
28.1	.930	.926	.921	.916	.911	.905	.900	.895	.890	.884	.879
28.2	.934	.929	.924	.919	.914	.909	.904	.898	.893	.887	.882
28.3	.937	.932	.928	.922	.917	.912	.907	.902	.896	.891	.885
28.4	.941	.936	.931	.926	.921	.915	.910	.905	.900	.894	.888
28.5	.944	.939	.934	.929	.924	.919	.914	.908	.903	.897	.892
28.6	.947	.943	.938	.932	.927	.922	.917	.912	.906	.901	.895
28.7	.951	.946	.941	.936	.931	.925	.920	.915	.909	.904	.898
28.8	.954	.949	.944	.939	.934	.929	.924	.918	.913	.907	.901
28.9	.958	.953	.948	.942	.937	.932	.927	.921	.916	.910	.905
29.0	.961	.956	.951	.946	.941	.935	.930	.925	.919	.914	.908
29.1	.964	.959	.954	.949	.944	.939	.933	.928	.923	.917	.911
29.2	.968	.963	.958	.952	.947	.942	.937	.931	.926	.920	.914
29.3	.971	.966	.961	.956	.950	.945	.940	.935	.929	.923	.918
29.4	.975	.969	.964	.959	.954	.949	.943	.938	.932	.927	.921
29.5	.978	.973	.968	.962	.957	.952	.947	.941	.936	.930	.924
29.6	.981	.976	.971	.966	.960	.955	.950	.944	.939	.933	.927
29.7	.985	.980	.974	.969	.964	.959	.953	.948	.942	.937	.931
29.8	.988	.983	.978	.972	.967	.962	.957	.951	.946	.940	.934
29.9	.991	.986	.981	.976	.970	.965	.960	.954	.949	.943	.937
30.0	.995	.990	.985	.979	.974	.968	.963	.958	.952	.946	.941
30.1	.998	.993	.988	.983	.977	.972	.966	.961	.955	.950	.944
30.2	1.002	.996	.991	.986	.980	.975	.970	.964	.959	.953	.947
30.3	1.005	1.000	.995	.989	.984	.978	.973	.968	.962	.956	.950
30.4	1.008	1.003	.998	.993	.987	.982	.976	.971	.965	.959	.954
30.5	1.012	1.006	1.001	.996	.990	.985	.980	.974	.969	.963	.957
30.6	1.015	1.010	1.005	.999	.994	.988	.983	.977	.972	.966	.960
30.7	1.018	1.013	1.008	1.003	.997	.992	.986	.981	.975	.969	.963
30.8	1.022	1.017	1.011	1.006	1.000	.995	.990	.984	.978	.972	.967

TABLE XXI. — TABLE OF CUBED COSINES.[1]

Angle.	Cosine^3.	Angle.	Cosine^3.	Angle.	Cosine^3.
1°	1.000	29°	.688	57°	.161
2	.998	30	.649	58	.149
3	.997	31	.649	59	.137
4	.993	32	.610	60	.125
5	.988	33	.590	61	.114
6	.983	34	.570	62	.103
7	.978	35	.550	63	.0396
8	.971	36	.529	64	.0842
9	.963	37	.509	65	.0754
10	.955	38	.489	66	.0671
11	.945	39	.469	67	.0596
12	.935	40	.449	68	.0526
13	.925	41	.429	69	.0460
14	.913	42	.410	70	.0400
15	.901	43	.391	71	.0345
16	.888	44	.372	72	.0295
17	.874	45	.353	73	.0250
18	.860	46	.335	74	.0209
19	.845	47	.317	75	.0173
20	.829	48	.300	76	.0142
21	.813	49	.282	77	.0114
22	.797	50	.265	78	.00900
23	.780	51	.249	79	.00695
24	.762	52	.233	80	.00523
25	.744	53	.218	81	.00383
26	.726	54	.203	82	.00270
27	.707	55	.189	83	.00181
28	.688	56	.175	84	.00114

[1] Cravath and Lansingh: Practical Illumination, p. 17.

TABLE XXII.

The following table is intended to facilitate the calculation of the illumination at points in vertical and horizontal planes. For use in computing horizontal illumination " l_v " signifies the height of the illuminant above the horizontal plane containing the reference point, l_h the horizontal distance from a point vertically below the illuminant to the point of reference, "θ" the angle of the beam measured from the vertical which falls upon the reference point and " K_1 " the factor by which the intensity of this beam must be multiplied to obtain the horizontal illumination. When computing vertical illumination " l_v" denotes the vertical height of the illuminant above the point of reference, " l_h " its horizontal distance from the point of reference, " θ " has the same significance as above and " K_2 " is the factor by which the intensity at the angle θ is multiplied to obtain the vertical illumination.

l_h	l_v = 6 ft.			l_v = 7 ft.			l_v = 8 ft.			l_v = 9 ft.		
	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2
0	0° 0′	.0278	.0000	0° 0′	.0204	.0000	0°	.0156	.0000	0°	.0127	.0000
1	9° 30′	.0266	.0045	8° 10′	.0198	.0028	7° 10′	.0152	.0019	6° 20′	.0122	.0014
2	18° 30′	.0237	.0079	16° 0′	.0180	.0052	14°	.0143	.0036	12° 30′	.0115	.0025
3	26° 30′	.0200	.0100	23° 10′	.0158	.0068	20° 30′	.0129	.0048	18° 30′	.0106	.0035
4	33° 40′	.0160	.0106	29° 50′	.0133	.0071	26° 30′	.0112	.0056	24°	.00945	.0042
5	39° 50′	.0125	.0104	35° 30′	.0110	.0078	32°	.0094	.0059	29° 10′	.00823	.0046
6	45° 0′	.0099	.0099	40° 40′	.00893	.0076	36° 50′	.00800	.0060	33° 40′	.00710	.0047
7	49° 20′	.0077	.0090	45° 0′	.00727	.00727	41° 10′	.00670	.0059	37° 50′	.00610	.00469
8	53° 10′	.0060	.00802	48° 50′	.00582	.00667	45°	.00552	.00552	41° 40′	.00488	.00459
9	56° 20′	.00473	.00688	52° 10′	.00471	.00609	48° 20′	.00460	.00515	45°	.00436	.00430
10	59° 0′	.00380	.00629	55°	.00388	.00549	51° 20′	.00381	.00475	48°	.00366	.00410
11	61° 20′	.00308	.00557	57° 30′	.00316	.00495	54°	.00318	.00437	50° 40′	.00315	.00383
12	63° 30′	.00247	.00497	59° 50′	.00260	.00448	56° 20′	.00266	.00401	53° 10′	.00266	.00356
13	65° 10′	.00206	.00442	61° 40′	.00219	.00402	58° 20′	.00226	.00364	55° 10′	.00230	.00326
14	66° 50′	.00169	.00396	63° 30′	.00181	.00366	60° 10′	.00192	.00333	57° 20′	.00195	.00303
15	68° 10′	.00143	.00355	65°	.00146	.00331	61° 50′	.00164	.00305	59°	.00169	.00280
16	69° 30′	.00119	.00321	66° 20′	.00132	.00300	63° 20′	.00139	.00280	60° 40′	.00146	.00258
17	70° 30′	.00104	.00290	67° 40′	.00102	.00273	64° 50′	.00120	.00256	62°	.00128	.00238
18	71° 30′	.00089	.00263	68° 50′	.00097	.00250	66°	.00105	.00235	63° 30′	.00110	.00221
19	72° 30′	.00076	.00240	69° 50′	.00084	.00229	67° 10′	.00092	.00217	64° 40′	.00097	.00204
20	73° 20′	.00066	.00220	70° 40′	.00074	.00210	68° 10′	.00081	.00200	65° 50′	.00085	.00189
21	74° 0′	.00058	.00201	71° 30′	.00065	.00194	69° 10′	.00070	.00185	66° 50′	.00075	.00176
22	74° 40′	.00051	.00185	72° 20′	.00057	.00179	70°	.00063	.00171	67° 50′	.00066	.00164
23	75° 20′	.00045	.00171	73° 10′	.00050	.00165	70° 50′	.00055	.00159	68° 40′	.00060	.00153
24	76° 0′	.00038	.00158	73° 50′	.00044	.00154	71° 30′	.00050	.00148	69° 30′	.00053	.00143
25	76° 30′	.00035	.00147	74° 20′	.00040	.00143	72° 20′	.00044	.00138	70° 10′	.00048	.00133

l_h	l_v = 10 ft.			l_v = 11 ft.			l_v = 12 ft.			l_v = 13 ft.		
	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2
0	0	.0100	....	0°	.00828	.00000	0°	.00695	.00000	0°	.00591	.00000
1	5° 30′	.0099	....	5° 10′	.00817	.00008	4° 40′	.00687	.00005	4° 20′	.00586	.00004
2	11° 20′	.00945	....	10° 20′	.00787	.00145	9° 30′	.00665	.00112	8° 50′	.00571	.00090
3	16° 40′	.00880	....	15° 20′	.00740	.00205	14°	.00635	.00157	13°	.00549	.00127
4	21° 50′	.00800	....	20°	.00688	.00250	18° 30′	.00592	.00200	17° 10′	.00517	.00161
5	26° 30′	.00717	....	24° 30′	.00621	.00285	22° 40′	.00548	.00230	21°	.00483	.00184
6	31°	.00629	....	28° 40′	.00558	.00306	26° 30′	.00496	.00247	24° 50′	.00442	.00206
7	35°	.00549	....	32° 30′	.00496	.00316	30° 10′	.00447	.00258	28° 20′	.00406	.00218
8	38° 40′	.00477	.00382	36°	.00438	.00318	33° 40′	.00400	.00267	31° 40′	.00365	.00226
9	42°	.00412	.00369	39° 20′	.00384	.00315	36° 50′	.00356	.00266	34° 40′	.00330	.00225
10	45°	.00353	.00353	42° 20′	.00334	.00305	39° 50′	.00312	.00263	37° 30′	.00297	.00225
11	47° 50′	.00302	.00346	45°	.00295	.00295	42° 30′	.00278	.00255	40° 20′	.00263	.00224
12	50° 10′	.00264	.00315	47° 30′	.00255	.00278	45°	.00245	.00245	42° 40′	.00236	.00217
13	52° 30′	.00226	.00295	49° 50′	.00222	.00264	47° 20′	.00216	.00236	45°	.00208	.00208
14	54° 30′	.00197	.00275	51° 50′	.00196	.00248	49° 20′	.00190	.10222	47° 10′	.00186	.00201
15	56° 20′	.00171	.00256	53° 50′	.00170	.00234	51° 20′	.00169	.00212	49° 20′	.00164	.00194
16	58°	.00149	.00238	55° 50′	.00146	.00221	53° 10′	.00151	.00200	50° 50′	.00149	.00182
17	59° 30′	.00131	.00221	57° 10′	.00132	.00205	54° 50′	.00133	.00189	52° 40′	.00132	.00174
18	61°	.00114	.00206	58° 30′	.00118	.00191	56° 20′	.00118	.00178	54° 10′	.00119	.00165
19	62° 10′	.00102	.00191	60°	.00104	.00180	57° 40′	.00107	.00167	55° 40′	.00106	.00156
20	63° 30′	.00089	.00179	61° 10′	.00093	.00168	59°	.00095	.00157	57°	.00096	.00148
21	64° 30′	.00089	.00167	62° 30′	.00081	.00158	60° 20′	.00084	.00149	58° 10′	.00087	.00139
22	65° 30′	.00072	.00156	63° 30′	.00073	.00148	61° 50′	.00075	.00141	59° 20′	.00079	.00131
23	66° 30′	.00065	.00146	64° 30′	.00066	.00139	62° 30′	.00068	.00132	60° 30′	.00071	.00125
24	67° 20′	.00057	.00136	65° 20′	.00060	.00130	63° 30′	.00062	.00125	61° 30′	.00064	.00121
25	68° 10′	.00052	.00126	66° 10′	.00055	.00123	64° 20′	.00056	.00117	62° 30′	.00058	.00112

l_h	$l_v = 14$ ft.			$l_v = 15$ ft.			$l_v = 16$ ft.			$l_v = 17$ ft.		
	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2
0	0°	.00510	.00000	0°	.00445	.00000	0°	.00391	.00000	0°	.00346	.00000
1	4° 10′	.00505	.00004	3° 50′	.00442	.00003	3° 30′	.00388	.00002	3° 20′	.00344	.00020
2	8° 10′	.00491	.00072	7° 40′	.00432	.00059	7° 10′	.00382	.00048	6° 40′	.00338	.00039
3	12° 10′	.00476	.00104	11° 20′	.00419	.00084	10° 40′	.00370	.00070	10°	.00330	.00058
4	16°	.00453	.00131	14° 50′	.00402	.00105	14°	.00357	.00089	13° 10′	.00320	.00074
5	19° 40′	.00426	.00152	18° 30′	.00378	.00128	17° 20′	.00340	.00106	15° 50′	.00307	.00081
6	23° 10′	.00397	.00169	21° 50′	.00356	.00143	20° 30′	.00320	.00119	19° 30′	.00290	.00104
7	26° 30′	.00366	.00181	25°	.00331	.00154	23° 40′	.00302	.00132	22° 20′	.00274	.00112
8	29° 40′	.00333	.00190	28°	.00307	.00162	26° 30′	.00279	.00139	25° 10′	.00256	.00120
9	32° 40′	.00305	.00195	31°	.00279	.00169	29° 30′	.00258	.00145	27° 50′	.00239	.00126
10	35° 30′	.00274	.00196	33° 40′	.00256	.00171	32°	.00238	.00149	30° 30′	.00221	.00131
11	38° 10′	.00247	.00195	36° 20′	.00233	.00172	34° 30′	.00219	.00150	32° 50′	.00205	.00132
12	40° 40′	.00222	.00193	38° 40′	.00212	.00170	36° 50′	.00200	.00154	35° 10′	.00189	.00133
13	42° 50′	.00202	.00186	40° 50′	.00192	.00166	39° 30′	.00181	.00154	37° 20′	.00174	.00132
14	45°	.00180	.00180	43°	.00174	.00162	41° 10′	.00167	.00146	39° 30′	.00159	.00131
15	47° 10′	.00160	.00175	45°	.00157	.00157	43° 10′	.00152	.00142	41° 30′	.00145	.00129
16	48° 50′	.00146	.00167	46° 50′	.00143	.00152	45°	.00138	.00138	43° 10′	.00134	.00125
17	50° 30′	.00131	.00159	48° 30′	.00130	.00146	46° 40′	.00128	.00133	45°	.00122	.00122
18	52° 10′	.00118	.00152	50° 10′	.00116	.00140	48° 20′	.00114	.00129	46° 50′	.00110	.00119
19	53° 40′	.00106	.00145	51° 40′	.00106	.00134	49° 50′	.00105	.00123	48° 10′	.00102	.00115
20	55°	.00097	.00138	53° 10′	.00096	.00128	51° 20′	.00095	.00119	49° 40′	.00094	.00111
21	56° 20′	.00087	.00131	54° 30′	.00087	.00122	52° 40′	.00087	.00114	51°	.00086	.00106
22	57° 30′	.00079	.00124	55° 40′	.00080	.00116	54°	.00080	.00109	52° 20′	.00079	.00102
23	58° 40′	.00072	.00118	56° 50′	.00073	.00111	55° 10′	.00073	.00105	53° 30′	.00073	.00098
24	59° 40′	.00066	.00112	58°	.00066	.00106	56° 20′	.00067	.00100	54° 40′	.00067	.00095
25	60° 40′	.00060	.00106	59°	.00061	.00101	57° 20′	.00062	.00095	55° 50′	.00061	.00091

l_h	l_v = 18 ft.			l_v = 19 ft.			l_v = 20 ft.			l_v = 21 ft.		
	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2
0	0°	.00309	.00000	0°	.00278	.00000	0°	.00250	.00000	0°	.00227	.00000
1	3° 10′	.00307	.00017	3°	.00276	.00014	2° 50′	.00249	.00012	2° 40′	.00226	.00011
2	6° 20′	.00303	.00034	6°	.00272	.00029	5° 40′	.00246	.00024	5° 30′	.00224	.00022
3	9° 30′	.00296	.00050	9°	.00266	.00042	8° 30′	.00241	.00036	8° 10′	.00220	.00032
4	12° 30′	.00288	.00063	12°	.00259	.00055	11° 20′	.00236	.00047	10° 50′	.00214	.00042
5	15° 30′	.00276	.00076	14° 50′	.00250	.00067	14°	.00228	.00057	13° 20′	.00209	.00049
6	18° 30′	.00265	.00089	17° 40′	.00240	.00078	15° 40′	.00220	.00066	16°	.00202	.00058
7	21° 20′	.00250	.00098	20° 10′	.00229	.00084	19° 20′	.00210	.00075	18° 30′	.00194	.00065
8	24°	.00235	.00105	22° 50′	.00217	.00091	21° 50′	.00200	.00080	20° 50′	.00185	.00070
9	26° 30′	.00228	.00110	25° 20′	.00204	.00097	24° 10′	.00190	.00085	23° 10′	.00176	.00075
10	29° 10′	.00206	.00115	27° 50′	.00191	.00103	26° 40′	.00179	.00089	25° 30′	.00167	.00079
11	31° 20′	.00194	.00117	30°	.00180	.00105	28° 50′	.00168	.00093	27° 40′	.00158	.00083
12	33° 40′	.00178	.00118	32° 20′	.00167	.00106	31°	.00158	.00095	29° 50′	.00148	.00086
13	35° 50′	.00165	.00118	34° 20′	.00156	.00106	33°	.00148	.00096	31° 50′	.00139	.00087
14	38°	.00152	.00119	36° 20′	.00145	.00106	35°	.00138	.00097	33° 40′	.00130	.00087
15	39° 50′	.00140	.00117	38° 20′	.00134	.00106	36° 50′	.00129	.00096	35° 30′	.00122	.00087
16	41° 40′	.00129	.00115	40° 10′	.00123	.00105	38° 40′	.00119	.00095	37° 20′	.00114	.00087
17	43° 20′	.00119	.00112	41° 50′	.00114	.00103	40° 20′	.00111	.00094	39°	.00106	.00086
18	45°	.00109	.00109	43° 30′	.00105	.00101	42°	.00103	.00092	40° 40′	.00098	.00086
19	46° 30′	.00101	.00105	45°	.00098	.00098	43° 30′	.00096	.00090	42° 10′	.00092	.00084
20	48°	.00093	.00102	46° 30′	.00090	.00096	45°	.00088	.00088	43° 40′	.00086	.00082
21	49° 20′	.00086	.00099	47° 50′	.00083	.00093	46° 20′	.00082	.00086	45°	.00080	.00080
22	50° 40′	.00079	.00096	49° 10′	.00077	.00090	47° 50′	.00077	.00084	46° 20′	.00074	.00078
23	52°	.00072	.00092	50° 30′	.00071	.00087	49°	.00071	.00081	47° 40′	.00069	.00076
24	53° 20′	.00066	.00089	51° 40′	.00065	.00084	50° 10′	.00066	.00079	48° 50′	.00064	.00074
25	54° 20′	.00061	.00086	52° 50′	.00060	.00081	51° 20′	.00061	.00077	50°	.00060	.00072

l_h	$l_v = 22$ ft.			$l_v = 23$ ft.			$l_v = 24$ ft.			$l_v = 25$ ft.		
	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2	θ	K_1	K_2
0	0°	.00207	.00000	0°	.00189	.00000	0°	.00174	.00000	0°	.00160	.00000
1	2° 30′	.00206	.00008	2° 30′	.00188	.00008	2° 20′	.00173	.00007	2° 20′	.00159	.00007
2	5° 10′	.00205	.00018	5°	.00187	.00016	4° 50′	.00172	.00014	4° 30′	.00158	.00013
3	7° 50′	.00201	.00028	7° 30′	.00184	.00024	7° 10′	.00169	.00022	6° 50′	.00156	.00019
4	10° 20′	.00196	.00036	9° 50′	.00181	.00032	9° 30′	.00166	.00028	9° 10′	.00154	.00025
5	12° 50′	.00191	.00044	12° 20′	.00176	.00039	11° 50′	.00162	.00034	11° 20′	.00151	.00030
6	15° 20′	.00185	.00051	14° 40′	.00170	.00045	14°	.00158	.00039	13° 30′	.00147	.00035
7	17° 40′	.00178	.00057	16° 50′	.00165	.00050	16° 10′	.00153	.00044	15° 40′	.00143	.00040
8	20°	.00171	.00062	19° 10′	.00159	.00055	18° 30′	.00148	.00049	17° 40′	.00138	.00044
9	22° 20′	.00163	.00066	21° 20′	.00153	.00059	20° 30′	.00142	.00053	19° 50′	.00133	.00048
10	24° 30′	.00155	.00070	23° 30′	.00146	.00063	22° 40′	.00136	.00057	21° 50′	.00127	.00052
11	26° 30′	.00148	.00073	25° 30′	.00139	.00066	24° 40′	.00130	.00060	23° 50′	.00122	.00055
12	28° 40′	.00140	.00077	27° 30′	.00132	.00069	26° 30′	.00124	.00062	25° 40′	.00117	.00057
13	30° 40′	.00132	.00079	29° 30′	.00125	.00071	28° 30′	.00118	.00064	27° 30′	.00112	.00058
14	32° 40′	.00124	.00080	31° 20′	.00118	.00072	30° 20′	.00112	.00065	29° 30′	.00106	.00060
15	34° 20′	.00117	.00080	33° 10′	.00112	.00073	32°	.00106	.00066	31°	.00101	.00061
16	36° 10′	.00109	.00080	34° 50′	.00105	.00073	33° 40′	.00100	.00066	32° 40′	.00095	.00062
17	37° 40′	.00103	.00079	36° 30′	.00099	.00073	35° 20′	.00094	.00067	34° 10′	.00090	.00061
18	39° 20′	.00096	.00079	38°	.00093	.00072	36° 50′	.00089	.00067	35° 50′	.00085	.00061
19	40° 50′	.00090	.00078	39° 30′	.00087	.00072	38° 20′	.00083	.00066	37° 10′	.00081	.00061
20	42° 20′	.00084	.00076	41° 20′	.00081	.00071	39° 50′	.00078	.00066	38° 40′	.00076	.00061
21	43° 40′	.00079	.00075	42° 20′	.00076	.00070	41° 10′	.00074	.00065	40°	.00072	.00060
22	45°	.00073	.00073	43° 40′	.00071	.00069	42° 30′	.00070	.00064	41° 20′	.00068	.00059
23	46° 20′	.00068	.00071	45°	.00067	.00067	43° 50′	.00066	.00063	42° 40′	.00064	.00059
24	47° 30′	.00063	.00070	46° 10′	.00063	.00065	45°	.00062	.00062	43° 50′	.00061	.00058
25	48° 40′	.00059	.00069	47° 20′	.00059	.00064	46° 10′	.00058	.00061	45°	.00057	.00057

TABLE XXIII. — TABLE GIVING THE NUMBER OF SOLID ANGULAR UNITS SUBTENDED BY ZONES OF A SPHERE MEASURED FROM ITS VERTICAL AXIS.

0°– 5°	.024	0°–50°	2.244
0°–10°	.096	0°–55°	2.679
0°–15°	.214	0°–60°	3.142
0°–20°	.379	0°–65°	3.628
0°–25°	.589	0°–70°	4.134
0°–30°	.842	0°–75°	4.657
0°–35°	1.136	0°–80°	5.192
0°–40°	1.471	0°–85°	5.735
0°–45°	1.840	0°–90°	6.283

TABLE XXIV. — TABLE GIVING MEAN ANGLE FROM VERTICAL CONTAINING FLUX OF DIRECT ILLUMINATION.

l_v = Height of illuminants above reference plane.
Area = Area of reference plane in square feet.

l_v feet.	Area.										
	100	150	200	250	300	350	400	450	500	550	600
6	43°	49°	53°	56°	58°	60°	62°	63°	65°	66°	67°
8	35	41	45	48	51	53	55	56	58	59	60
10	29	35	39	42	44	47	49	50	52	53	54
12	25	30	34	37	39	41	43	45	46	48	49
14	22	26	30	33	35	37	39	41	42	43	45
16	19	23	27	29	31	33	35	37	39	40	41
18	17	21	24	26	28	30	32	34	35	36	38

l_v feet.	Area.										
	700	800	900	1000	1100	1200	1300	1400	1500	1600	1800
6	68°	69°	70°	71°	72°	73°	74°	74°	75°	75°	76°
8	62	63	65	66	67	68	69	69	70	71	72
10	56	58	59	61	62	63	64	65	65	66	67
12	51	53	55	56	57	58	59	60	61	62	63
14	47	49	51	52	53	54	55	56	57	58	60
16	43	45	47	48	49	51	52	53	54	54	56
18	40	42	43	45	46	47	48	49	51	52	53

l_v feet.	Area.										
	2000	2200	2600	3000	3400	3800	4200	4600	5000	6000	7000
6	77°	77°	78°	79°	80°	80°	81°	81°	81°	82°	82°
8	73	73	74	75	76	77	78	78	79	80	80
10	68	69	71	72	73	74	74	75	76	77	78
12	65	66	67	68	70	71	72	73	74	75	76
14	61	62	64	66	67	68	69	70	71	72	73
16	58	59	61	63	64	65	66	67	68	70	71
18	55	56	58	60	61	63	64	65	66	68	69

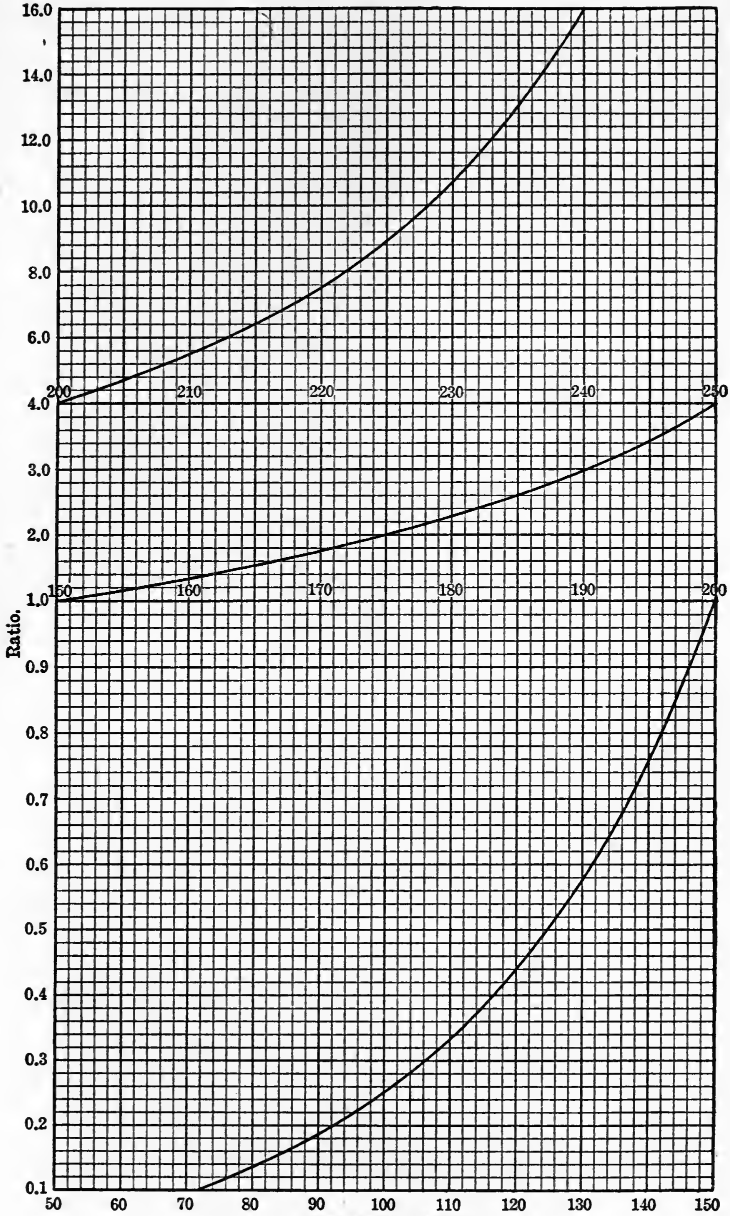


FIG. 115. Ratio chart for photometer bar of 300 divisions, giving the ratio of the candle-power of the lamp at 300 to that of the lamp at 0 for settings between 50 and 250.

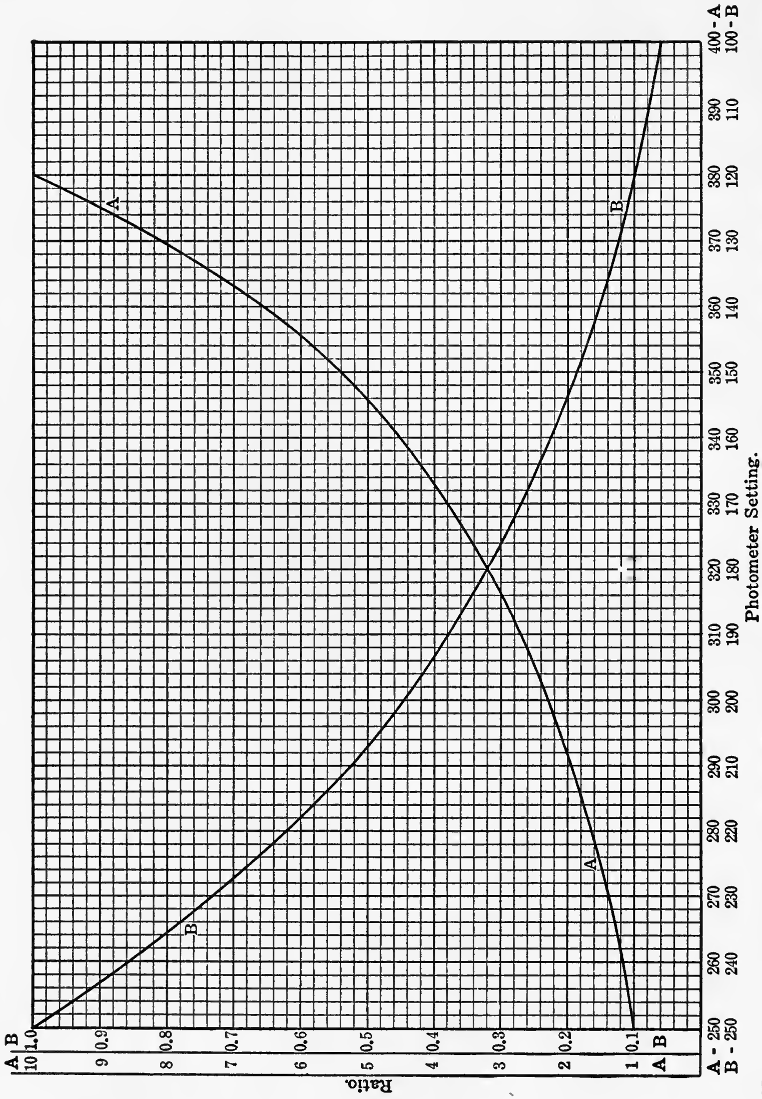


FIG. 116. Ratio chart for photometer bar of 500 divisions, giving the ratio of the candle-power of the lamp at 500 to that of the lamp at 0 for settings between 100 and 380.

INDEX

750 net

2.00